NEHRU COLLEGE OF ENGINEERING AND RESEARCH CENTRE
(NAAC Accredited)
(Approved by AICTE, Affiliated to APJ Abdul Kalam Technological University, Kerala)

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

COURSE MATERIAL

EE409 : ELECTRICAL MACHINE DESIGN

VISION OF THE INSTITUTION

To mould true citizens who are millennium leaders and catalysts of change through excellence in education.

MISSION OF THE INSTITUTION

NCERC is committed to transform itself into a center of excellence in Learning and Research in Engineering and Frontier Technology and to impart quality education to mould technically competent citizens with moral integrity, social commitment and ethical values.

We intend to facilitate our students to assimilate the latest technological know-how and to imbibe discipline, culture and spiritually, and to mould them in to technological giants, dedicated research scientists and intellectual leaders of the country who can spread the beams of light and happiness among the poor and the underprivileged.

ABOUT DEPARTMENT

- Established in: 2006
- Course offered: B.Tech Electrical and Electronics Engineering
- Approved by AICTE New Delhi and Accredited by NAAC
- Affiliated to the University of Dr. A P J Abdul Kalam Technological University.

DEPARTMENT VISION

To excel in technical education and research in the field of Electrical & Electronics Engineering by imparting innovative engineering theories, concepts and practices to improve the production and utilization of power and energy for the betterment of the Nation.

DEPARTMENT MISSION

1. To offer quality education in Electrical and Electronics Engineering and prepare the students for professional career and higher studies.
2. To create research collaboration with industries for gaining knowledge about real-time problems.
3. To prepare students with sound technical knowledge.
4. To make students socially responsible.

PROGRAM OUTCOME (PO'S)

Engineering Graduates will be able to:

PO 1. Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

PO 2. Problem analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO 3. Design/development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO 4. Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO 5. Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO 6. The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO 7. Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO 8. Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO 9. Individual and team work: Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO 10. Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO 11. Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO 12. Life-long learning: Recognize the need for, and have the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOME(PSO'S)

1. Apply Science, Engineering, Mathematics through differential and Integral Calculus, Complex Variables to solve Electrical Engineering Problems.
2. Demonstrate proficiency in the use of software and hardware to be required to practice electrical engineering profession.
3. Apply the knowledge of Ethical and Management principles required to work in a team as well as to lead a team.

COURSE OUTCOME

After the completion of the course the student will be able

CO 1	To impart knowledge on principles of design of static and rotating electrical machines
CO 2	To impart knowledge on principles of design of Transformers
CO 3	To impart knowledge on principles of design of DC machines
CO 4	To impart knowledge on principles of design of Synchronous machines
CO 5	To impart knowledge on principles of design of Induction electrical machines
CO 6	To give a basic idea about computer aided design (CAD) and finite element method

CO VS PO'S AND PSO'S MAPPING

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO 1	PSO 2	PSO 3
CO 1	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 2	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 3	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 4	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 5	3	3	2	2	-	-	-	-	-	-	-	2	2	2	2
CO 6	3	3	2	2	-	-	-	-	-	-	-	2	2	2	1

Note: H-Highly correlated=3, M-Medium correlated=2, L-Less correlated=1

SYLLABUS

Module	Contents	Hours	Sem. Exam Marks
I	Principles of electrical machine design - General design considerations - specifications of machines - types of enclosures - types of ventilation - heating - short time rating - overload capacity - temperature rise time curve - hot spot rating. Magnetic circuit calculation - calculation of field ampere turns - air gap mmf - effect of slot and ventilating duct - active iron length - mmf for teeth - real and apparent flux densities - mmf per pole Magnetic Leakage Calculation- Effects of Leakage. Armature Leakage –Components. Unbalanced Magnetic Pull-Practical aspects of unbalanced magnetic pull	8	15%
II	Design of transformers - single phase and three phase transformers - distribution and power transformers - output equation - core design - window area - window space factor - overall dimensions of core. Windings – no. of turns - current density - conductor section - Cooling of transformers	6	15%
III	Design of DC machines - output equation - specific loading - choice of speed and no of poles - calculation of main dimensions - choice of type of winding - number of slots - number of conductors per slot-current density - conductor section - slot insulation -	8	15%
IV	Design of synchronous machines - specific loading - output equation - main dimensions - types of winding - number of turns - number of slots and slot design - field design for water wheel and turbo alternators - cooling of alternators.	6	15%
V	Design of three phase induction motors - main dimensions - stator design - squirrel cage and slip ring types - number of stator and rotor slots - rotor bar current - design of rotor bar - end ring current - design of end ring - design of slip ring rotor winding.	7	20%
VI	Introduction to computer aided design. Analysis and synthesis methods -hybrid techniques. Introduction to Finite element method - historical background, applications, advantages. Study of new computer aided machine software using Finite Element Case study: Complete design of an ac machine –steps.(Assignment only)	7	20%

QUESTION BANK

1. Write a note on factors for general design consideration for electrical machine design.
2. Discuss about enclosure. Also explain the various types of enclosures used in electrical machines.
3. Examine the different types of ventilations in electrical machines.
4. Write a short note on
   i. Temperature rise time curve
   ii. Hot spot rating of an electrical machine
5. Write a note on :
   a) Leakage flux
   b) Fringing
   c) Stacking Factor
6. Discuss about the airgap MMF for magnetic circuit. Also determine the calculation of airgap MMF for magnetic circuit.
7. Explain the effect of slot and ventilating ducts.
8. Compare the reluctance of slotted armature with that of smooth armature surface
9. Discuss the MMF for teeth and also explain the various method for estimation.
10. Derive the real and apparent flux densities for teeth of a machine.
11. Discuss the MMF per pole and also write the calculation of MMF per Pole at various portion of the magnetic circuit.
12. Discuss how magnetic leakage developed in winding and its effects. Also write a note on magnetic leakage calculation.
13. Explain the armature leakage and also discuss its components.
14. Explain the unbalanced magnetic pull and also determine the expression for it.
15. The initial temperature of a machine is 45°C. Calculate the temperature of the machine after 1.2 hour if its final steady temperature rise is 85°C and the heating time constant is 2.4 hours. The ambient temperature is 25°C.
16. A Field coil has a dissipating surface of 1600cm2 and a length of mean turn of 110cm. It dissipates a loss of 160W , the emissivity being 34 W/m2 °C. Estimate the final steady temperature rise of the coil and its time constant if the cross section of the coil is 10*5 cm.
17. The temperature rise of a loaded transformer is 25°C after one hour and 37.5°C after 2 hours. Calculate the final steady full load temperature rise and the heating time constant of the transformer. When disconnected , the temperature falls from the final steady value of 40°C in 1.5 hours. Also find its cooling time constant. Take the ambient temperature as 30°C.
18. The temperature rise of a full loaded DC machine is 15°C after one hour and 25°C after 2 hours. Calculate
   (a) final steady temperature rise and time constant.
   (b) steady temperature rise after one hour at 50% overload, from cold. Assume that the final temperature rise on 50% overload is 90°C.
19. A 15 kW, 230 V, 4 pole DC machine has the following data: Armature diameter = 0.25m

, armature core length = 0.125m , length of airgap at pole centre = 2.5 mm , flux per pole = 11.7wb , pole arc/pole pitch = 0.66. Calculate the MMF required for air gap (a) if the armature surface is smooth (b) if the armature is slotted and gap contraction factor is 1.18.

20. Determine the airgap length of a DC machine having the following particulars.
    Slot pitch = 25mm , slot width = 10mm , gross core length = 0.12m , carter's coefficient for slot and duct = 0.32 , gap density at pole centre = 0.7wb/m2 , field mmf/pole = 3900AT, mmf required for iron parts of magnetic circuit = 800AT. There are 1 ventilating ducts each 10mm wide.
21. Determine the ampere turns required for the airgap length of a DC machine having the following data.
    Slot pitch = 6.5cm , slot width = 10mm , gross core length = 40cm , airgap length = 0.5cm , carter's coefficient = 0.82 for opening/gap length = 1.0 and carter's coefficient = 0.72 for opening/gap length = 2.0 , average value of flux density in airgap = 0.63T , field form factor = 0.7 . There are 5 ventilating ducts each 1cm wide.
22. Determine the ampere turns/pole required for the airgap length of a DC machine having the following data.
    tooth width = 18.5mm , slot width = 13.5mm , radical length of airgap = 6.4mm , width of core packets = 50.8mm , width of ventilating ducts = 9.5mm. Carter's coefficient for slots and ducts = 0.27 and 0.21 respectively , maximum gap density = 0.8T. Neglect theampere turns for the iron parts.
23. Calculate the apparent flux density at a section of the tooth of the armature of a DC machine with the following data at that section. Slot pitch = 2.4cm , slot width = 1.2cm , armature core length including 5 ducts each 1.0cm wide = 38cm , stacking factor = 0.92 , true flux density in the teeth at the section is 2.2T for which the ampere turns/m is 70000.

Module II

1. Give a constructional details of single phase transformers.
2. Give a note on Distribution and Power transformers.
3. Derive the output equation of a single phase core type transformer.
4. Derive the output equation of a three phase core type transformer.
5. Write a short note on :
    a) Winding design
    b) Window space factor
    c) Window area
    d) Yoke design
    e) Number of Turns
    f) Current density
6. Determine the ratio of net core area to the area of circumscribing circle for a square core transformer.

7. Evaluate the ratio of net core area to the area of circumscribing circle for a two stepped core transformer.
8. Write a short note on design of core of transformers. Why stepped core construction is

preferred for transformer.

9. Draw the horizontal and vertical cross sectional view of single transformers and three transformers and mark the overall dimensions.
10. Design a Tank with tubes for transformer.
11. Explain the different methods of cooling of transformers with neat diagrams.
12. A 50 KVA, 2200/220V 1-Φ transformer has 550 turns on the primary side. If stacking factor Ki = 0.9 and maximum flux density 1.1 Wb/m2 . Calculate for 2 stepped core (i) core flux (ii) net core area (iii) Diameter of circumscribing circle.
13. Calculate the core and window area required for a 1000 kVA, 6600/400V, 50 hz, 1-Φ core type transformer. Assume a maximum flux density of 1.25 Wb/m2 and a current density 2.5A/mm2 . Voltage per turn is 30 V and window space factor is given as 0.32
14. Calculate the kVA output of a single phase transformer from the following data:
    Core height/distance between core centres = 2.8
    Diameter of circumscribing circle / distance between core centres = 0.56
    Net iron area / area of circumscribing circle = 0.7
    Current density = 2.3 a/mm2
    Window space factor = 0.27
    Frequency = 50 hz
    Flux density of core = 1.2 wb/m2
    Distance between core centres = 0.4 m
15. Calculate the main dimensions of a single phase transformer 200 kVA having frequency of 50 hz. A cruciform core is used with distance between adjacent limbs equal to 1.6 times the width of core laminations. Assume the window space factor of 0.32, current density of 3A/mm2, voltage per turn of 14 V, maximum flux density of 1.1 Wb/m2 and stacking factor 0.9. The width of the largest stamping is 0.85d and the net iron area is 0.56d2 in a cruciform core.
16. Determine the main dimensions of the core, the number of turns and the cross section of the conductors for a 5kVA, 11000/400V, 50 Hz 1-Φ core type distribution transformer. The net conductor area in the window is 0.6 times the net cross section of iron in the core. Assume a square cross section of the core, a flux density of 1 Wb/m2, a current density 1.4 A/mm2, and a window space factor 0.2. The height of window is 3 times its width.
17. Determine the dimensions of core and yoke for a 200kVA, 50 Hz, 1**ϕ** core type transformer. A cruciform core is used with the distance between adjacent limbs equal to 1.6 times the width of core lamination. Assume voltage per turn 14V, maximum flux density1.1Wb/m2, window space factor 0.32, current density 3A/mm2 and stacking factor 0.9. The net iron area is 0.56d2in cruciform core where d is the diameter of circumscribing circle. Also the width of the largest stamping is 0.85d.
18. Calculate the approximate overall dimension for a 200kVA, 6600/400 V, 50 Hz, 3 phase core type transformer. The following data are assumed:
    emf/turn=10V, maximum flux density =1.3Wb/m2, current density=2.5A/mm2, window space factor=0.3, overall height=overall width, stacking factor=0.9, Use a 3 stepped core, width of largest stamping=0.9d and net iron area=0.6d2 where d is the diameter of circumscribing circle.
19. Determine the dimensions of the core, the number of turns, the cross section area of conductors in primary and secondary windings of a 100kVA, 2200/480V, single phase,

core type transformer, to operate at a frequency of 50Hz, by assuming the following data. Approximate volt per turn=7.5V, maximum flux density =1.2wb/m2. Ratio of effective cross sectional area of core to square of diameter of circumscribing circle is 0.6. Ratio of height to width of window is 2. Window space factor=0.28. Current density=2.5A/mm2.

20. Determine the main dimensions of the core, the no of turns and cross section area of the conductor for a 5kVA, 11/0.4 kV, 50 Hz, single phase core type distribution transformer. The net area in window is 0.6 times the net cross section of iron in the core. Assume a square cross section for the core, a flux density 1Wb/m2, a current density of 1.4A/mm2 and a window space factor 0.2. The height of window is 3 times the width.
21. The tank of a 1250kVA natural oil cooled transformer has the dimensions length, width and height as 1.55m*0.65m*1.85m respectively. The full load loss is 13.1kW. Find the number of tubes for this transformer assuming specific heat dissipation is 6 W/m2-:C and 6.5 W/m2-:C due to radiation and convection respectively. Improvement in convection due to provision of tubes=40%, temperature rise=40: C; length of each tube=1m; diameter of tubes=50mm. Neglect the top and bottom surfaces of the tank as regards cooling.
22. Estimate the main dimensions including winding conductor area of a 300kVA, 6600/440V, 50Hz three phase delta/star core type transformer. A suitable core with three steps having a circumscribing circle of 0.25m diameter and leg spacing of 0.4m is available. The voltage/turn=8.5V, current density=2.5A/mm2, window space factor=0.28 and stacking factor is 0.9.

Module III

1. Derive the output equation of DC machine.
2. Explain the various factors to be considered while selecting the number of poles of DC machine.
3. Explain the i) choice of Bav ii) choice of ac iii) choice of D iv) choice of L in the case of DC machine.
4. Discuss the choice of speed and number of poles for DC machine.
5. A 5kW, 250V, 4 pole, 1500rpm DC shunt connected generator is designed to have a square pole face. The specific magnetic and electrical loading are 0.42wb/m2 and 15000AC/m respectively. Find the main dimensions of the machine. Assume that the pole arc is 0.66 times the pole pitch and full load efficiency as 0.87.
6. A 50kW, 220V, 4 pole, 600rpm DC shunt connected generator is designed to have a square pole face. The specific magnetic and electrical loading are 0.83wb/m2 and 30000AC/m respectively. Find the main dimensions of the machine. Assume that the pole arc is 0.67 times the pole pitch and full load armature voltage is 3% of the rated terminal voltage and the field current is 1% of rated full load current.
7. Explain the factors on which separation of D & L depends. Also explain the factors to be considered while selecting the values for armature core diameter and armature core length.
8. A 5kW, 230V, 4 pole, 1500rpm DC shunt connected generator is designed to have a square pole face. The specific magnetic and electrical loading are 0.42wb/m2 and 15000AC/m respectively. Find the main dimensions of the machine. Assume that the pole arc is 0.6 times the pole pitch and full load efficiency as 0.88.
9. Explain the steps to design aspects of series field winding of a DC machine.

10. Explain the steps to design aspects of shunt field winding of a DC machine.
11. Find the main dimensions and the number of poles of a 37kW, 230V and 1400rpm shunt motor so that a square pole face is obtained. The average gap density is 0.5wb/m2 and the ampere conductors per metre are 22000. The ratio of pole arc to pole pitch is 0.7.
12. Calculate the main dimensions of a 20HP, 1000rpm and 400V DC motor. Given that Bav=0.37wb/m2 and ac=16000 ampere conductor/m. Assume an efficiency of 90%.
    Choose with reasons a suitable number of poles for a 400kW, 250V, 250rpm shunt generator having an armature diameter of 1.2m and a length of 0.3m. The maximum gap density is 0.9wb/m2 and ratio of pole arc to pole pitch is 0.7.
    a) Explain why increase in number of poles reduce the weight of copper in the armature and at the same time reduces the outhang of the winding so that overall length of the machine is reduced.
    b) Comment on the statement "the total weight of iron in DC machine decreases with increase in number of poles".
13. Find the main dimensions of a 200kW, 250V, 6 pole, 1000rpm generator. The maximum value of flux density in the gap is 0.87wb/m2 and the ampere conductors per metre of armature periphery are 31000. The ratio of pole arc to pole pitch is 0.67 and the efficiency is 91%. Assume the ratio of length of core to pole pitch=0.75.
14. A 600kW, 500V, 900rpm DC shunt connected generator is designed to have a square pole face. The specific electrical loading are 35000AC/m and average gap density 0.6wb/m2 and respectively. Find the main dimensions of the machine, number of poles and length of air gap. Assume that the pole arc is 0.75 times the pole pitch and full load efficiency as 91%. The following are the design constraints: peripheral speed≯40m/s, frequency of flux reversals≯50Hz, current per brush arm≯400A and armature mmf per pole≯7500A. The mmf required for air gap is 50% of armature mmf and gap contraction factor is 1.15.

MODULE IV

1. Derive the output equation of a synchronous machines
2. Discuss the term number of turns and number of slots in synchronous machines. Also discuss the slot design.
3. Make a design procedure for water wheel alternator
4. List the factors to be considered in selection of Bav and ac in synchronous machines
5. With suitable diagrams explain in detail about cooling of alternators
6. Design the stator frame of a 500kVA , 6.6 kV , 50Hz , 3phase, 12 pole star connected salient pole alternator giving following information.
    g) Internal diameter and gross length of the frame
    h) Number of stator conductors
    i) Number of stator slots and conductor per slot

    Specific magnetic and electric loading may be assumed as 0.56 tesla and 2600ac/m respectively. Peripheral speed must be less than 40m/s and slot must be less than 1200.
7. The following is the design data available for a 1250 kVA, 3phase, 50Hz, 3300V, star connected , 300rpm, alternator of salient pole type:
    Stator bore = 0.19m, stator core length = 0.335m, pole arc /pole pitch = 0.66 , turns per phase=150, single layer concentric winding with 5 conductors per slot, short circuit ratio = 1.2. Assume that the distribution of gap flux is rectangular under the pole arc with zero

values in the interpolar region. MMF required for airgap is 0.88 of no load field mmf and the gap contraction factor is 115. Calculate a) specific magnetic loading b) armature mmf per pole c) gap density over pole arc d) air gap length

8. A 2500kVA, 225rpm, 3 phase, 60Hz, 2400V, star connected salient pole alternator has the following design data
   Stator bore = 2.5m, core length = 0.44m , slots per pole per phase = 3, conductor per slot = 4 , circuits per phase = 2, leakage factor=1.2 , winding factor=0.95. The flux density in pole core is 1.5wb/m2 , the winding depth is 30mm , the ratio of full load field mmf to armature mmf is 2, field winding space factor is 0.84 and the field winding dissipates 1800 W/m2 of inner and outer surface without the temperature rise exceeding the permissible limit. Leave 30mm for insulation, flanges and height of pole shoe along the height of pole.
   Find a) flux per pole b) length and width of pole c) winding height and d) pole height

MODULE V

1. Derive the output equation of a three phase induction motor
2. Determine the various parameters involved in designing of Stator for induction machine
3. Explain the rules for selecting number of rotor slots in three phase induction motor
4. How do you separate D and L from the volume D2L of a three phase induction motor
5. State and explain the factors involved in selection of airgap length in induction motor
6. Determine the main dimension and number of turns per phase of 3.7 kW, 400 V, 4 pole , 50Hz, squirrel cage induction motor to be started by a star delta starter. Average flux density in the gap is 0.45 wb/m2 , ampere conductor per meter is 23000 , efficiency = 85% , PF = 0.84 , winding factor = 0.955 , stacking factor = 0.9. The machine is to be sold at a competitive price and therefore choose the main dimensions if required. Assume suitable data accordingly if required.
7. Estimate the stator core dimensions, number of stator slots and number of stator conductors per slot for a 100 kW, 3300 V, 50 Hz, 12 pole star connected slip ring induction motor. Assume average gap density = 0.4 wb/m2 , conductor per metre = 25000 A/m, efficiency = 0.9, PF = 0.9 , winding factor = 0.96. Choose main dimensions to give best power factor. The slot loading should not exceed 500 ampere condutors.
8. Make a design on rotor bars and slots for an three phase induction motor.
9. Make a design on wound rotor for an three phase induction motor.

MODULE VI

1. Explain the analysis and synthesis method of design for CAD
2. Discuss the new CAD machine software using finite element
3. Explain about introduction to finite element method, its advantages, disadvantages and applications.
4. Describe in detail about introduction of CAD and its various types of software
5. Discuss about Gluing Function for the Analysis of FEA Tools
6. Explain the Meshing Process in FEA

MODULE 1

Principles of electrical machine design - General design considerations - specifications of machines - types of enclosures - types of ventilation - heating - short time rating - overload capacity - temperature rise time curve - hot spot rating.

Magnetic circuit calculation - calculation of field ampere turns - air gap mmf - effect of slot and ventilating duct - active iron length - mmf for teeth - real and apparent flux densities - mmf per pole Magnetic Leakage Calculation- Effects of Leakage. Armature Leakage –Components. Unbalanced Magnetic Pull-Practical aspects of unbalanced magnetic pull

References - 'A course in Electrical Machine Design' by A.K. Sawhney

- 'Electrical Machine Design' by Nagoor Kani

PRINCIPLES OF EMD

INTRODUCTION

- The **basic design** of an **electrical machine** involves the dimensioning of the magnetic circuit, **electrical** circuit, insulation system etc., and is carried out by applying analytical equations, temperature rise and lower cost. Also they are to be reliable and durable

PRINCIPLES OF EMD

- Involves application of science and technology to produce cost-effective, durable, quality and efficient machines.
- Machines should be designed as per standard specifications.

GENERAL DESIGN CONSIDERATIONS

- Magnetic circuit or flux path: Should establish the required amount of minimum MMF. The core loss should be less
- Electric circuit or windings: Should ensure that required EMF is induced in the windings. The copper loss should be less.
- Insulation: Should ensure proper insulation between machine parts
- Cooling system/ventilation: should ensure that the machine operates at specified temperature
- Machine parts: Successful design includes optimization of cost of manufacturing and operating and maintenance charges
- Other factors:
  - Customer needs
  - National and international standards
  - Convenience in production and transportation
  - Environmental conditions

SPECIFICATIONS OF MACHINES

- Specifications are the guidelines for the manufacturer to produce economic products without compromising quality.
- The standard specifications issued for the electrical machines include the following:
  - Standard ratings of the machines.
  - Types of enclosure
  - Standard dimensions of conductor to be used
  - Method of marking ratings and name plate details
  - Types of insulation and permissible temperature rise
  - Performance specifications to be met
  - Permissible loss and range of efficiency
  - Procedure for testing of machine parts and machines
  - Auxiliary equipment's to be provided
  - Cooling methods to be adopted

- Every country has a standards organisation to fix standard specifications.
- In India, Indian Standard Organisation(ISO) has laid down their specifications(ISI) for various products.
- The standards will be amended time to time, in order to include the latest developments in technology
- The name plate of rotating machine has to bear the following details as per ISI specifications:
  - kW or kVA rating of machine
  - Rated working voltage
  - Operating speed
  - Full load current
  - Class of insulation
  - Frame size
  - Manufactures name
  - Serial number of the product

LIMITATIONS IN DESIGN

1. Saturation of magnetic parts:

- Increased core losses and excitation at higher flux density resulting in higher cost for the field system.

2. Temperature rise:

- Increased temperature rise under higher output weakens the insulation and affects the life of machine.

3. Insulation:

- It should be able to withstand the electrical, mechanical and thermal stresses which are produced in the machine.

4. Mechanical strength:

- Specially in turbo machine due to large size and high speed.

5. Commutation :

- In DC machine output is limited because of commutation problem

Contd...

6. Efficiency:

- If high efficiency is the aim, the machine becomes costly. For lower efficiency higher running cost and temperature rise with associated problems.

7. Customer's specifications:

- Imposes limitations to identify criterion for best design

8. Power factor:

- Power factor imposes a limitation specially in case of 3 phase induction motor.

9. Standard specification:

- Specification is biggest strain on the design because of the both the manufacturer as well as the consumer cannot get away from them without satisfying them.

ENCLOSURES

- An Enclosure is a cabinet for electrical or electronic equipment to mount switches, knobs and displays and to prevent electrical shock to equipment users and protect the contents from the environment.
- Only part of the equipment which is seen by users.
- It protect machines against dust, dirt, moisture, chemicals and foreign bodies.
- But enclosure interfere with free entry of cool air into the machine.

TYPES OF ENCLOSURES

1. Open Type
   - Open Pedestal (OP)
   - Open End bracket (OEB)
2. Protected Type(P)
3. Screen Protected Type(SP)
4. Drip Proof Type (DP)
5. Splash Proof Type (SPLP)
   - Hose Proof Type (HP)
6. Pipe Ventilated /Duct Ventilated Type

Contd…

7. Totally Enclosed Type (TE)
   - Totally Enclosed Fan Cooled Type(TEFC)
   - Totally Enclosed Separately Air Cooled (TESAC)
   - Totally Enclosed Water or other liquid Cooled (TEWC)
   - Totally Enclosed Closed Air Circuit
   - Totally Enclosed Closed Gas Circuit
8. Flame Proof Type(FP)
9. Weather Proof Type (WP)
10. Water Tight (WT)
11. Submersible Type

1) OPEN TYPE

- It does not protect from dust, dirt and larger foreign bodies but **Facilitates in cooling**
- No restriction to ventilation
- Machine kept in clean and separate room
- Used in power station and substation

1.1) OPEN PEDESTAL (OP)

- Machine which has pedestal bearing supported independently of machine frame

1.2) OPEN END BRACKET (OEB)

- Machine having end bracket bearing which forms an integral part

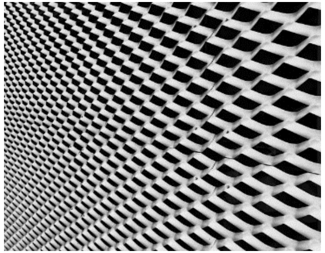
2) PROTECTED TYPE (P)

- Internal live parts and rotating parts are protected mechanically from accidental contact
- Ventilation is not materially obstructed
- Used in Industrial purposes

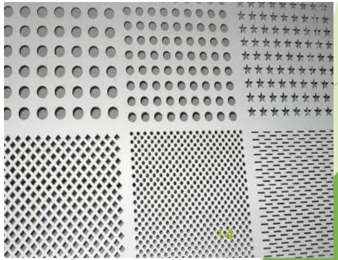
3) SCREEN PROTECTED TYPE (SP)

- Here openings provided for ventilation are covered with wire screen, expanded metal or other suitable perforated covers.
- Ventilation openings are not exceeding $3.25cm^2$ but not less than $0.6cm^2$ in area.
- It does not protect from dust or dirt but **protect from large bodies or insects.**
- Used in Industrial applications where dry clean conditions prevail.

Screen Wire



Expanded Metal



Perforated Metal Sheet

4) DRIP PROOF TYPE

- Openings for ventilation are so protected as to exclude vertically falling water or dirt
- Allows air to circulate through the windings for cooling.
- Used in damp situations such as for pumping sets

5) SPLASH PROOF TYPE (SPLP)

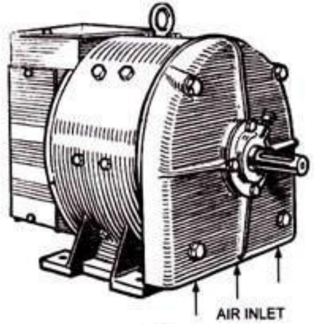
- Ventilating openings are so constructed that drops of liquid or solid particles falling at any angle between **vertically downward direction and 100˚ from that direction** cannot enter the machine, whether machine is running or at rest

5.1) HOSE PROOF TYPE(HSP)

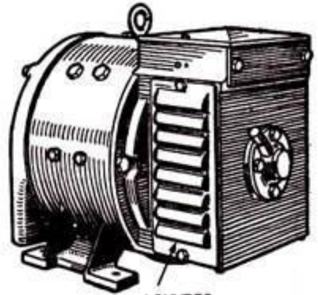
- A protected machine enclosed as to exclude the water when **washed by a hose** having a 9.5 mm diameter nozzle with maximum pressure 3.5kg/cm^2 for a period not exceeding 30 sec, from a minimum distance of 1.8m

6) PIPE VENTILATED/DUCT VENTILATED TYPE

- These are totally enclosed type machines in which to overcome the heat dissipation difficulties, a duct or pipe is provided through which clean air is led to the motor from outside the dust laden building or area.
- The cost of the piping may be overweighed by the saving in cost of motor, as motor of smaller size can be used with same output.
- Fresh clean air is brought to the motor by piping and drawn in through a big inlet, as illustrated in (i), and air is then expelled through louvers or taken away by pipe, as illustrated in (ii).
- Types:
  - With provision for inlet duct only
  - With provision for inlet and outlet ducts.
  - With provision for outlet duct only



(i)



(ii)

(d) Pipe-Ventilated Motor

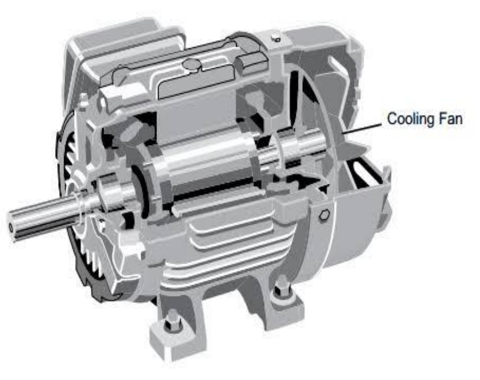
Fig. 1.112

7) TOTALLY ENCLOSED TYPE (TE)

- Have solid frame and end shield
- No openings for ventilation
- Get **cooled by Surface radiation** only
- No dirt or foreign matters can enter
- Used in coal handling plant , saw mills etc

7.1 TOTALLY ENCLOSED FAN COOLED TYPE (TEFC)

- Totally enclosed machine with cooling augmented by a fan driven by the motor itself, blowing external air over the cooling surface and/or through the cooling passages , if any, incorporated in the machine.
- Saw mills ,flour mills, cement works



7.2 TOTALLY ENCLOSED SEPERATELY AIR COOLED MACHINE(TESAC)

- Cooling augmented by separately driven fan blowing external air over the cooling surface and/or through the cooling passages

7.3 TOTALLY ENCLOSED WATER OR OTHER LIQUID-COOLED MACHINE(TEWC)

- Cooling augmented by water cooled or other liquid cooled surfaces embodied in the machine itself.

7.4 TOTALLY ENCLOSED CLOSED AIR CIRCUIT MACHINE

- Totally enclosed machine having special provision for cooling the enclosed air by passing it through its own cooler usually external to the machine
- Cooler→ Air , Water or Other suitable cooling medium

7.5 TOTALLY ENCLOSED CLOSED GAS CIRCUIT MACHINE

- Totally enclosed machine cooled by gas other than air

8) FLAME PROOF TYPE(FLP)

- Withstand explosion of the gas which may occur within it
- Ventilating openings in the machine are made long enough for the flame to be contained within the frame
- Used in : petroleum stations ,chemical plants

9) WEATHER PROOF MACHINE(WP)

- A machine so constructed that it can work without further protection from weather conditions specified by the purchaser

10) WATERTIGHT MACHINE(WT)

- A machine so constructed that it can withstand, without damage or sign of leakage, complete immersion in water to a depth of not less than 1m or subjection to external pressure of 0.1kg/cm^2 for a period of 1 hour

11) SUBMERSIBLE MACHINE

- A machine capable of working for an indefinitely long period when submerged under specified head

MODULE 1

Principles of electrical machine design - General design considerations - specifications of machines - types of enclosures - types of ventilation - heating - short time rating - overload capacity - temperature rise time curve - hot spot rating.

Magnetic circuit calculation - calculation of field ampere turns - air gap mmf - effect of slot and ventilating duct - active iron length - mmf for teeth - real and apparent flux densities - mmf per pole Magnetic Leakage Calculation- Effects of Leakage. Armature Leakage –Components. Unbalanced Magnetic Pull-Practical aspects of unbalanced magnetic pull

References - 'A course in Electrical Machine Design' by A.K. Sawhney

- 'Electrical Machine Design' by Nagoor Kani

COOLING AND VENTILATION

- When any machines are operating then there are losses occurring in the machine in various forms
- Losses leads to temperature rise
- The temperature rise at any part of the machine should not go beyond the permissible limit.
- Cooling system or ventilation should ensure that the machine operates at specified temperature.
- Cooling of electrical machines by means of air stream is known as ventilation.

TYPES OF VENTILATION

1. 1.1 Induced ventilation
   - Induced self ventilation
   - Induced ventilation with external fan

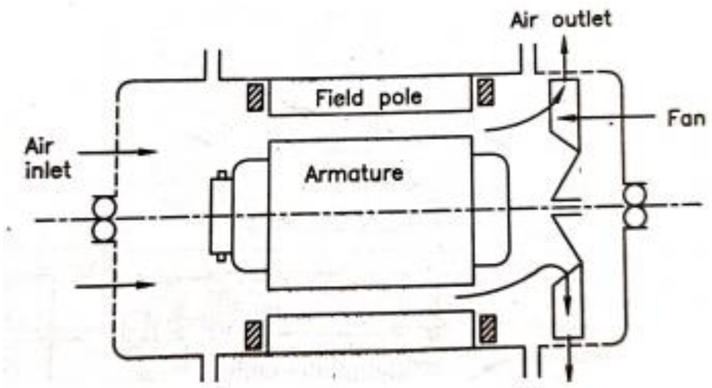
   1.2 Forced ventilation
   - Forced self ventilation
   - Forced ventilation with external fan
2. 2.1 Radial ventilation

   2.2 Axial ventilation

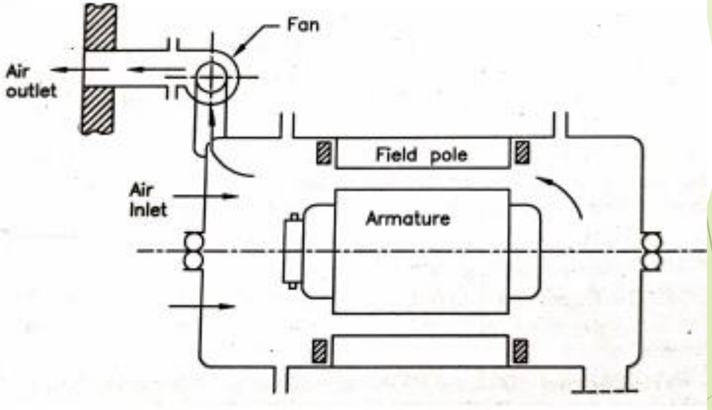
   2.3 Combined radial and axial ventilation

INDUCED VENTILATION

- Rotation of fan creates a decreased pressure inside the machine causing the air to be sucked into the machine as air flows from high pressure to low pressure.
- Then the air is circulated inside the machine and is pushed out into the atmosphere by the fan.
- Used in Small and Medium Power Outputs.



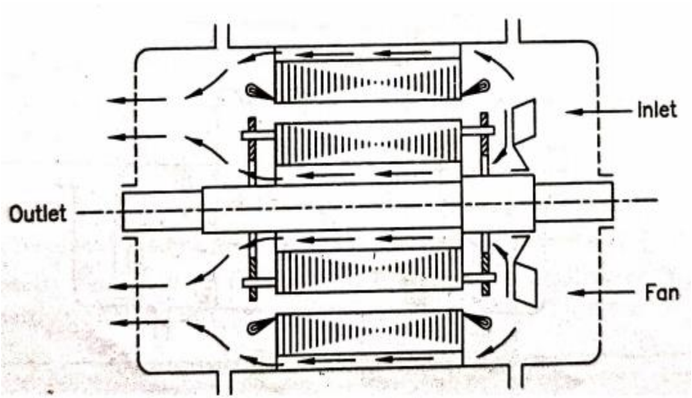
Induced self ventilation



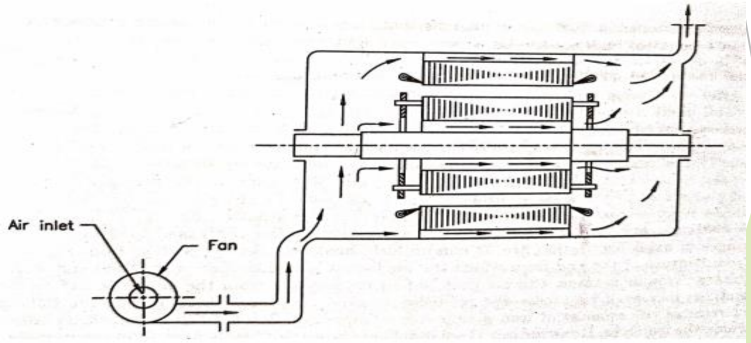
Induced ventilation with external fan

FORCED VENTILATION

- Fan sucks air from the atmosphere and forces it into the machine and finally it is then pushed out into the atmosphere.
- The temperature of the cooling air rises the in account of losses in the fan.
- Thus the amount of air required is higher



Forced self ventilation

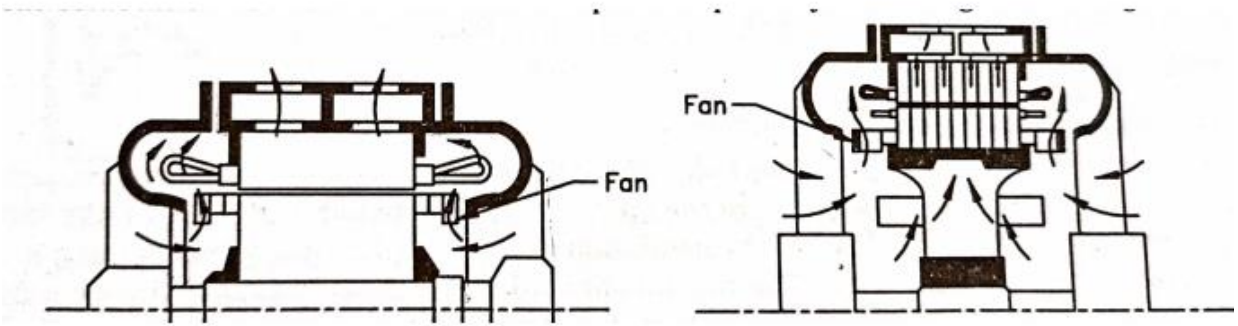


Forced ventilation with external fan

RADIAL VENTILATION

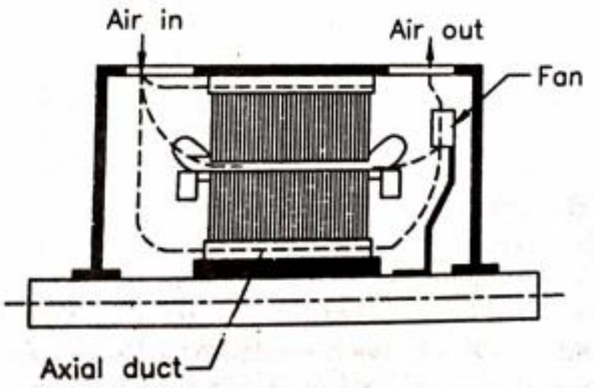
- This system is most commonly employed because the movement of rotor induces a natural centrifugal movement of air which may be augmented by provisions of fans if required.
- The method is suitable for rating less than 20kW.
- For larger machines the core is normally subdivided to provide radial ventilating ducts.
- The air now passes radially through these ducts, the path of the air in the ducts being parallel to the overhang
- Core is normally divided into stacks of 40 to 80mm thick, with ventilating ducts of width 10mm in between them
- With air flowing up the radial ducts only a layer 3mm wide in contact with the core walls is effective in cooling and the middle 4mm wide band contributes very little to cooling of the core
- Advantages:
  - Minimum energy loss for ventilation
  - Uniform temperature rise of machine
- Disadvantages:
  - Makes the machine length larger

RADIAL VENTILATION



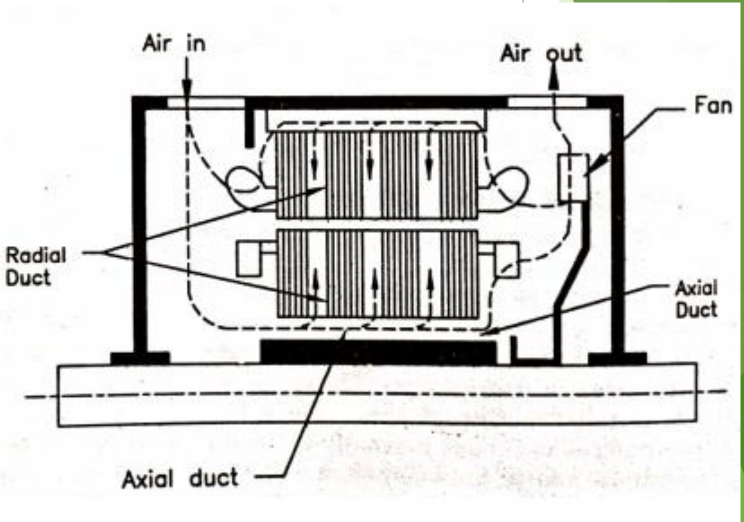
AXIAL VENTILATION

- Axial ducts are used
- Axial ducts arranged on rotor- simple axial system
- Axial ducts arranged on rotor and stator- double axial system
- Ducts are provided in stator / rotor or both in a direction parallel to the shaft axis
- Used for medium output and high speed application
- Holes are punched where considerable heat dissipation occurs
- Disadvantage
  - Non-uniform heat transfer
  - Increased iron loss



COMBINED RADIAL AND AXIAL VENTILATION

- Area of axial ducts to carry cooling air becomes larger , giving rise to large iron loss.
- Hence too minimize losses mixed radial and axial ventilation is used.
- The air is drawn into the machine from one end and passes through the ducts and finally rotor mounted fans force out the air.
- Used for large motors and small turboalternators.

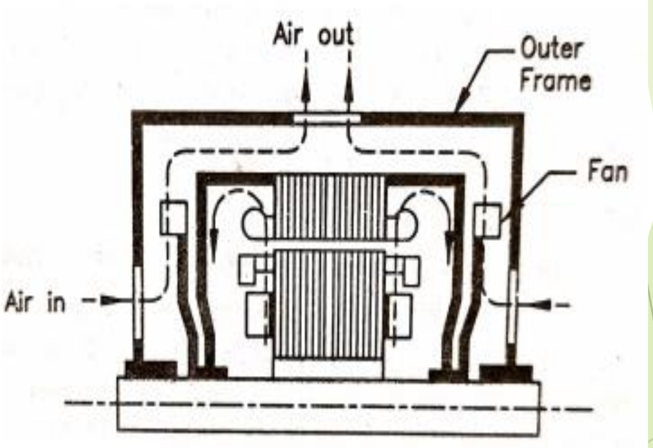


COOLING OF TOTALLY ENCLOSED MACHINE

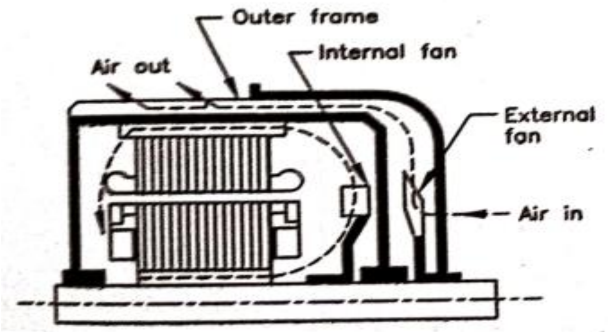
- Preferred-when air surrounding contains explosive gases and acid fumes that may destroy insulation
- In a totally enclosed machine the air inside the machine have no connection with the outside and all the heat developed inside should be dissipated into the surroundings
- Types-
  - Ventilated frame machine
  - Ventilated radiator machine

VENTILATED FRAME MACHINE

- A fan is mounted on the shaft outside the working parts of the machine and it blows air through the space between main housing and the thin cover plate.
- The fan pushes the air along the surface of the machine
- Suitable for power output less than 25kW.

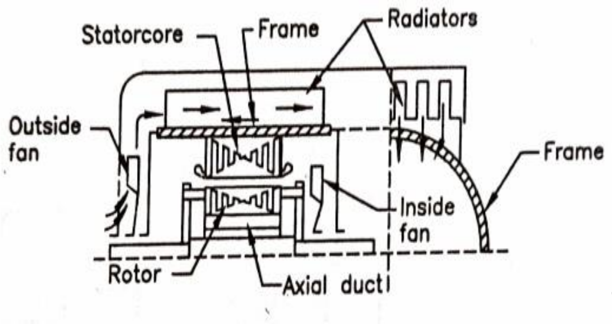


- For larger rating it is necessary to provide an internal fan in additional for circulation of air inside the machine to improve heat dissipation
- Air inside the machine- primary coolant
- Air outside the machine – secondary coolant



VENTILATED RADIATOR MACHINES

- Internal fan circulates air inside the machine
- External fan – sucks hot air from inside and pushes it to radiator(heat exchangers)- there the air is cooled by fans which are not integral part of machine and fed back to the machine.
- Suitable for power output upto 5MW



RATINGS OF MACHINE

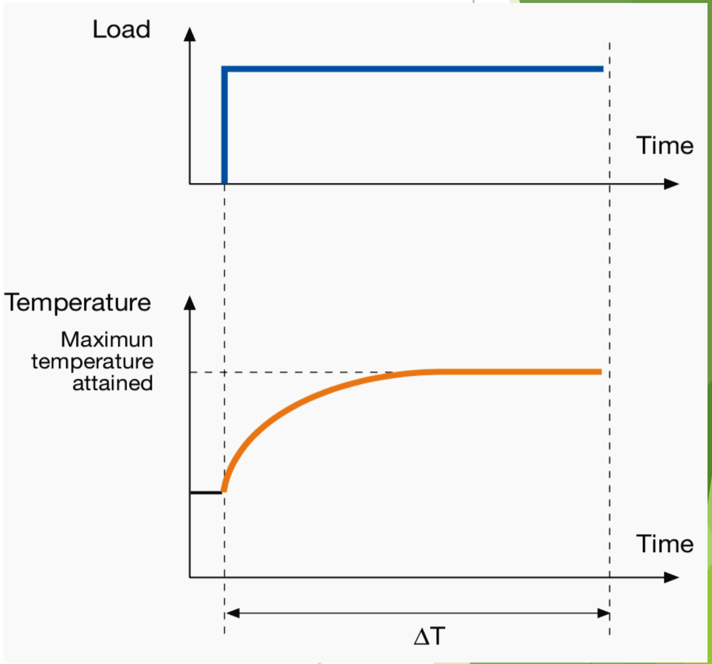
- The rating of an electrical machine is **power output** which is based upon certain definite conditions assigned to it.
- The rating is mainly **decided by the temperature rise** in the machine.
- Machine is rated on the basis of its thermal characteristics due to temperature rise.
- A **machine** can always be **overloaded to some extend** provided the **temperature rise** in the machine **does not exceed** the permissible value.
- Different ratings are defined for the machine depending upon the type of duty(load) and its duration.
- Majority of motor are designed for continuous loads.

DIFFERENT TYPES OF RATINGS

- Continuous Rating(Continuous Duty)
- Short Time Rating(Short Time Duty)
- Intermittent Rating(Intermittent Duty)

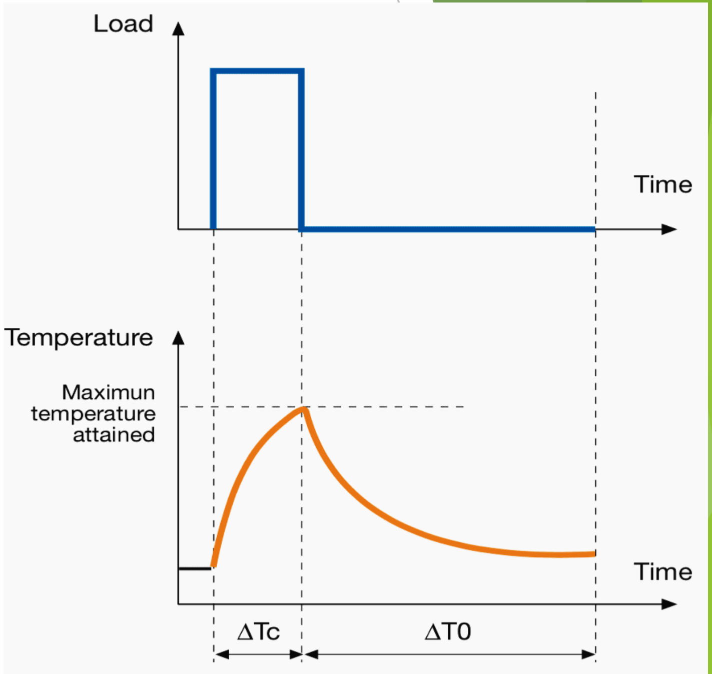
CONTINUOUS RATING

- In continuous duty, the duration of **load on machine is fairly long**
- **Continuous rating is the load** that may be carried by the machine for an **indefinite time without temperature rise** of any part exceeding the maximum permissible value.
- Continuous rating of a machine is the output which a machine should give for an indefinite time(continuously)without its temperature rise above permissible limits
- All portion of the machine attains its max. final steady temperature rise after certain time of its start
- Used in fans, pumps, industrial drives etc.



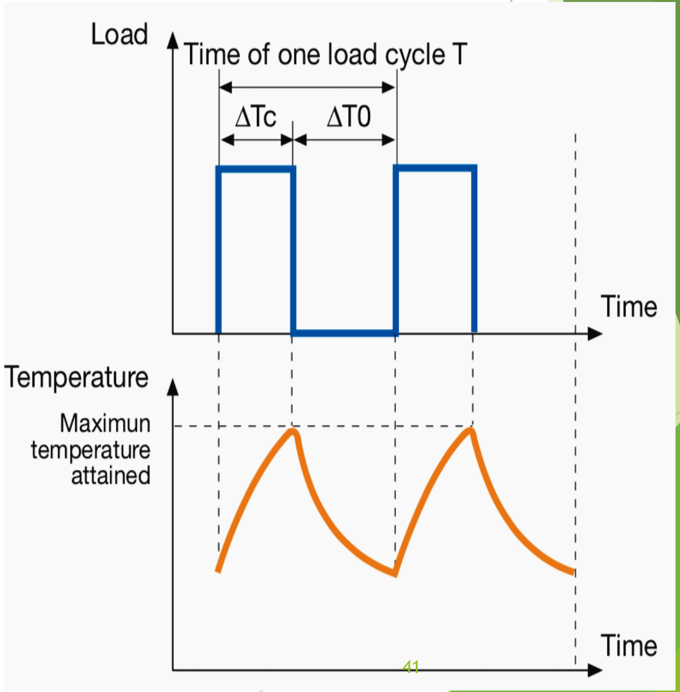
SHORT TIME RATING

- Short time rating of a machine can be defined as its output at which machine can **work for a specified period** without exceeding the maximum specified temperature rise in the machine
- The **working period** of the machine is **very short** so that the temperature rise in the machine is below its maximum permissible limit of temp rise
- The **no load period** or shut down period or rest period is so **long** so that the machine reaches to its cold condition
- For the machines with same dimensions the output of the machine with short time rating will be more than that of machine with continuous rating.
- Used in navigation lock gates, railway turn tables



INTERMITTENT RATING

- The intermittent rating of machine means operating condition during which the machine **works for short time load periods alternate with rest periods** i.e. machine works for a short period followed by a period of rest or no load
- For same dimension and same cooling conditions, a machine with intermittent loading have a larger output than a machine with continuous loading
- Used in: lifts, cranes, cutting tools etc.



HOT SPOT RATING

TEMPERATURE RISE TIME CURVE

Principles of electrical machine design - General design considerations - specifications of machines - types of enclosures - types of ventilation - heating - short time rating - overload capacity - temperature rise time curve - hot spot rating.

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TEMPERATURE RISE TIME CURVE

→ Heating & Cooling of Electrical Machine.

Assumption

① Total loss remains the same.

② Dissipation of heat energy is proportional to the difference b/w the hot part & cooling medium

③ Temp of cooling med remains constant.

$G \rightarrow$ weight of active part of machine (kg)

$Q \rightarrow$ Power loss or heat developed (J/s or W)

$h \rightarrow$ Specific heat J/kg °C

$S \rightarrow$ Cooling surface in m^2

$\lambda \rightarrow$ Specific heat dissipation $W/m^2 - °C$

$c = \frac{1}{\lambda} \rightarrow$ Cooling coefficient $°C - m^2/W$

θ = temp rise at any time t, °C.

θ_m = final steady temp rise while heating. °C.

θ_n - final steady temp rise while cooling °C.

θ_i - Initial temp rise over ambient medium °C.

τ_h - heating time constant, s

τ_c = cooling time constant, s

t = time, s.

heat developed $H = Q\,dt$ —— (1)

Heat stored = $G\,h\,d\theta$ —— (2)

Heat dissipated = $\lambda \times S \times \theta \times dt$ —— (3)

Heat produced = Heat stored + Heat dissipated

Heat developed = Heat stored + Heat dissipated —(4)

$$Q\,dt = Gh\,d\theta + \lambda S \theta\,dt$$

$$Q = Gh\frac{d\theta}{dt} + \lambda S\theta$$

$$\frac{Q}{Gh} = \frac{d\theta}{dt} + \frac{\lambda S\theta}{Gh}$$

$$\frac{d\theta}{dt} = \frac{Q}{Gh} - \frac{\lambda S\theta}{Gh}$$

$$d\theta = \left(\frac{Q}{Gh} - \frac{\lambda S\theta}{Gh}\right)dt$$

$$\therefore dt = \frac{d\theta}{\left(\frac{Q}{Gh} - \frac{\lambda S\theta}{Gh}\right)} \quad \text{—(5)}$$

Let $u = \frac{Q}{Gh} - \frac{\lambda S\theta}{Gh}$ —(6)

$$\frac{du}{d\theta} = -\frac{\lambda S}{Gh}$$

$$d\theta = -\frac{Gh}{\lambda S}du \quad \text{—(7)}$$

Put (7) & (6) in (5)

$$dt = \frac{-\frac{Gh}{\lambda S}du}{u}$$

$$= -\frac{Gh}{\lambda S}\frac{du}{u}$$

Integrating:

$$\int dt = -\frac{Gh}{\lambda S}\int\frac{du}{u}$$

$$t = -\frac{Gh}{\lambda S}\log_e u + K \quad \text{—(8)}$$

$$= -\frac{Gh}{\lambda s}\log_e\left(\frac{Q}{Gh} - \frac{\lambda S\theta}{Gh}\right) + k \quad \text{—(9)}$$

To find K, Put $t = 0$ and $\theta = \theta_i$

$$0 = -\frac{Gh}{\lambda S}\log_e\left[\frac{Q}{Gh} - \frac{\lambda S}{Gh}\theta_i\right] + K$$

$$K = \frac{Gh}{\lambda S}\log_e\left[\frac{Q}{Gh} - \frac{\lambda S}{Gh}\theta_i\right] \quad \text{—(10)}$$

Sub (10) in (9),

$$t = -\frac{Gh}{\lambda S}\log_e\left[\frac{Q}{Gh} - \frac{\lambda S\theta}{Gh}\right] + \frac{Gh}{\lambda S}\log_e\left[\frac{Q}{Gh} - \frac{\lambda S\theta_i}{Gh}\right]$$

$$= -\frac{Gh}{\lambda S}\left[\log_e\left(\frac{Q}{Gh} - \frac{\lambda S\theta}{Gh}\right) - \log_e\left(\frac{Q}{Gh} - \frac{\lambda S\theta_i}{Gh}\right)\right]$$

$$= -\frac{Gh}{\lambda S}\left[\log_e\frac{\left(\frac{Q}{Gh} - \frac{\lambda S\theta}{Gh}\right)}{\left(\frac{Q}{Gh} - \frac{\lambda S\theta_i}{Gh}\right)}\right]$$

$$= -\frac{Gh}{\lambda S}\left[\log_e\frac{\frac{\lambda S}{Gh}\left(\frac{Q}{\lambda S} - \theta\right)}{\frac{\lambda S}{Gh}\left(\frac{Q}{\lambda S} - \theta_i\right)}\right]$$

$$t = -\frac{Gh}{\lambda S}\left[\log_e\frac{\left(\frac{Q}{\lambda S} - \theta\right)}{\left(\frac{Q}{\lambda S} - \theta_i\right)}\right] \quad \text{—(11)}$$

If m/c temp. rise to maximum,

$$\left[\begin{array}{l} t = \infty,\ d\theta = 0 \\ \theta = \theta_m \end{array} \right.$$

Heat developed = Heat dissipated

$$Q\,dt = \lambda S \theta\, dt$$

$$Q = \lambda S \theta$$

$$\theta = \frac{Q}{\lambda S} \quad \text{— (12)}$$

Sub (12) in (11),

$$t = -\frac{Gh}{\lambda S} \log_e \frac{\theta_m - \theta}{\theta_m - \theta_i}$$

$$\tau_h = \frac{Gh}{\lambda S} \rightarrow \text{Heating time constant}$$

$$t = -\tau_h \log_e \frac{\theta_m - \theta}{\theta_m - \theta_i}$$

$$-\frac{t}{\tau_h} = \log_e \frac{\theta_m - \theta}{\theta_m - \theta_i}$$

$$\frac{\theta_m - \theta}{\theta_m - \theta_i} = e^{-t/\tau_h}$$

$$\theta_m - \theta = (\theta_m - \theta_i)\, e^{-t/\tau_h}$$

$$\theta_m - \theta = \theta_m e^{-t/\tau_h} - \theta_i e^{-t/\tau_h}$$

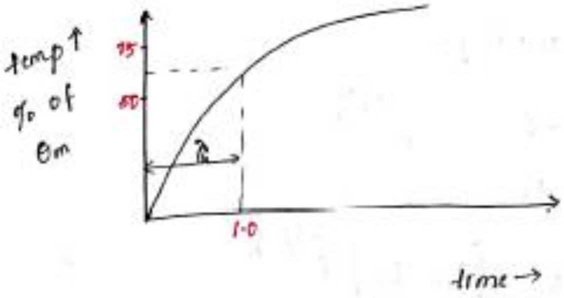
$$\theta = \theta_m - \theta_m e^{-t/\tau_h} + \theta_i e^{-t/\tau_h}$$

$$= \theta_m (1 - e^{-t/\tau_h}) + \theta_i e^{-t/\tau_h}$$

When m/c is started from cooling condⁿ,

cooling condⁿ → $\theta_i = 0$

$$\theta = \theta_m \left(1 - e^{-t/\tau_h}\right) \quad \text{--- (14)}$$



$t = \tau_h$

$$\theta = \theta_m \left(1 - e^{-1}\right) = 0.63\,\theta_m$$

Machine under cooling condition,

$$\theta = \theta_c \left(1 - e^{-t/\tau_c}\right) + \theta_i e^{-t/\tau_c}$$

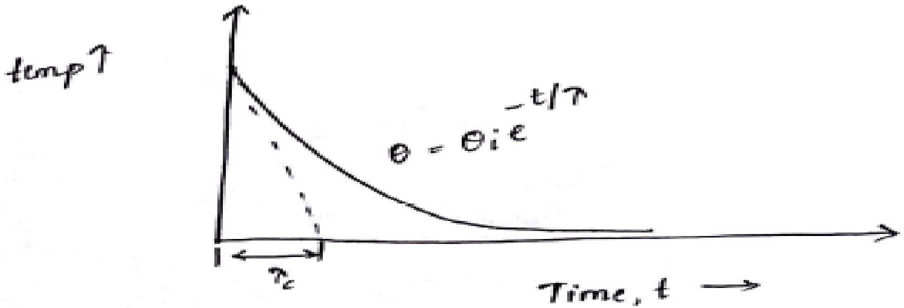
$\theta_c = 0$

$$\theta = \theta_i e^{-t/\tau_c}$$

$t = \tau_c$

$$\theta = \theta_i e^{-1}$$

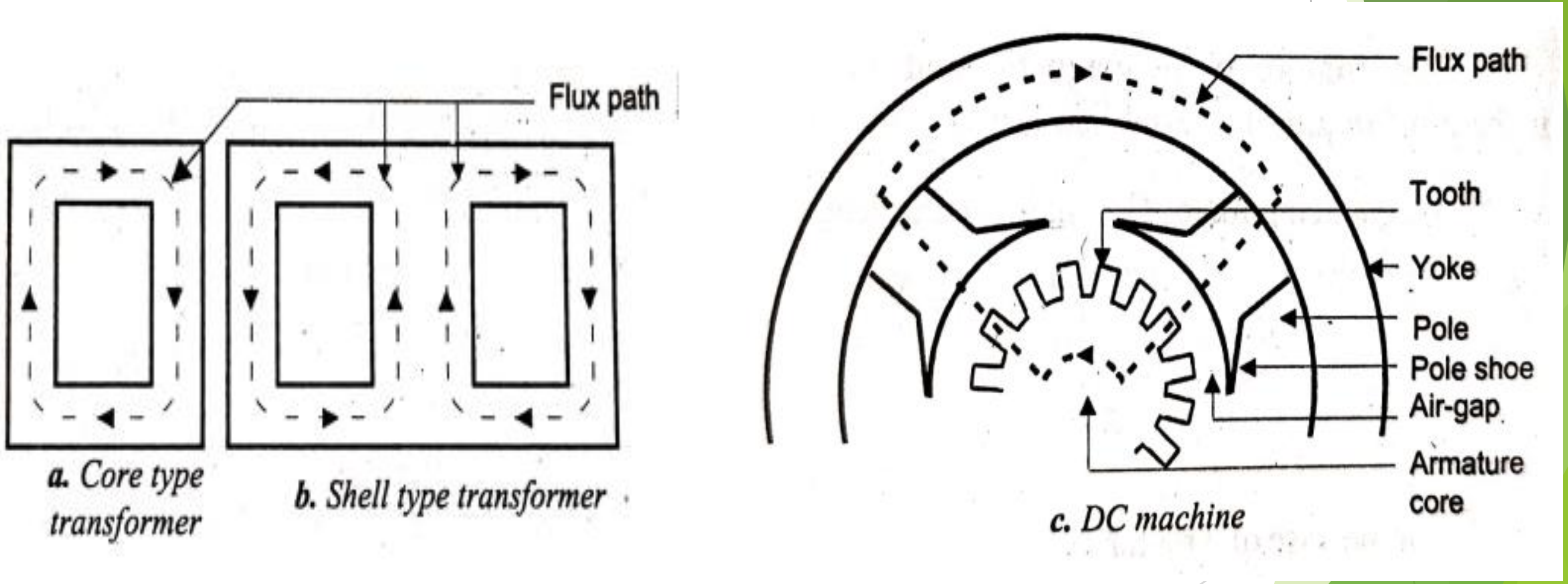
$$\theta = 0.36\, \theta_i$$



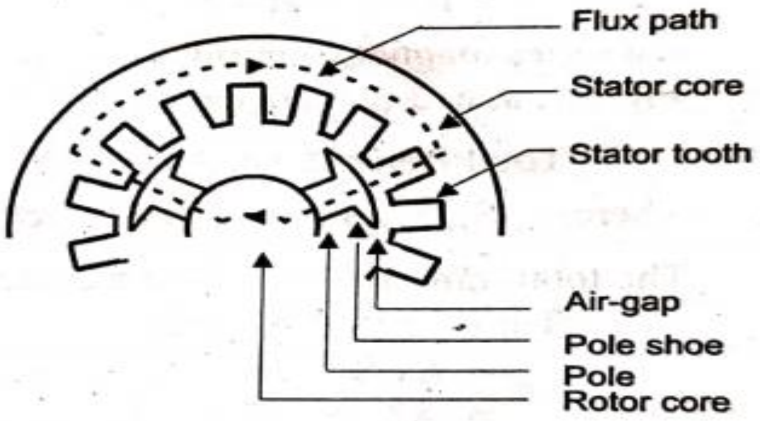
MAGNETIC CIRCUIT

- Magnetic circuit is the path of magnetic flux
- The MMF of the circuit creates flux in the path by overcoming the reluctance of the path
- Various elements in the flux path of:
  - Salient Pole Machine: Poles, pole shoes , air-gap, armature teeth, armature core and yoke
  - Non-Salient Pole Machine: stator core, stator teeth, air-gap, rotor teeth and rotor core
  - Transformer: core

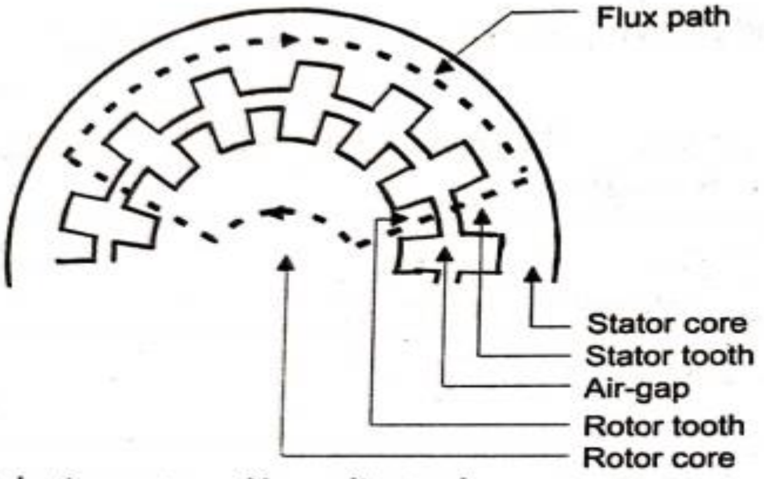
FLUX PATH


Flux path
a. Core type transformer
b. Shell type transformer
Flux path
Tooth
Yoke
Pole
Pole shoe
Air-gap
Armature core
c. DC machine

FLUX PATH



Salient pole synchronous machine



Induction motor or Non-salient pole synchronous machine

MAGNETIC CIRCUIT CALCULATION

- Involves the estimation of **reluctance(S), flux density(B) and mmf** for various sections of magnetic circuit
- The ultimate **aim** of magnetic circuit calculation i**s to estimate the total mmf required to establish the required flux** in a magnetic circuit
- The magnetic circuit is split into convenient parts which may be connected in series or parallel

PROCEDURE TO ESTIMATE MMF OF A SECTION OF MAGNETIC CIRCUIT

- Determine the **flux** in the concerned section from the knowledge of flux per pole
- Calculate the **area of cross section** of the section from the specified dimensions
- Ratio of flux and area of cross-section will give the **flux density, B** in this section
- For the calculated flux density ,B, determine **the mmf per unit length from the B-H curve**
- The **mmf for the concerned section** is given by the **product of length of the section and mmf per unit length**

Contd…

- The method looks quite simple but there are some parts in the magnetic circuit like **air-gap** and tapered **teeth** which present **complex magnetic problems**
- The **reluctance of the air-gap is modified or affected** due to **slots, radial ventilating ducts and non-uniform air-gaps**
- Dimensions of the tooth depend on the type of slot and it is not uniform, hence reluctance is also non-uniform
- Reluctance of air-gap in machine varies based on type of slot as,

  1) Reluctance of air-gap in machine with smooth armature

  2) Reluctance of air-gap in machines with open armature slots

1) RELUCTANCE OF AIR-GAP IN MACHINE WITH SMOOTH ARMATURE

- Rotating machines have a small air-gap between armature and pole surface
- For smooth armature surfaces, armature has closed slots
- Consider the iron surfaces of two sides of the air-gap to be smooth
- The flux is uniformly spread over the entire slot pitch and goes straight across the air-gap

L – Length of core

l_g - Air-gap length

y_s - slot pitch

w_s - width of slot

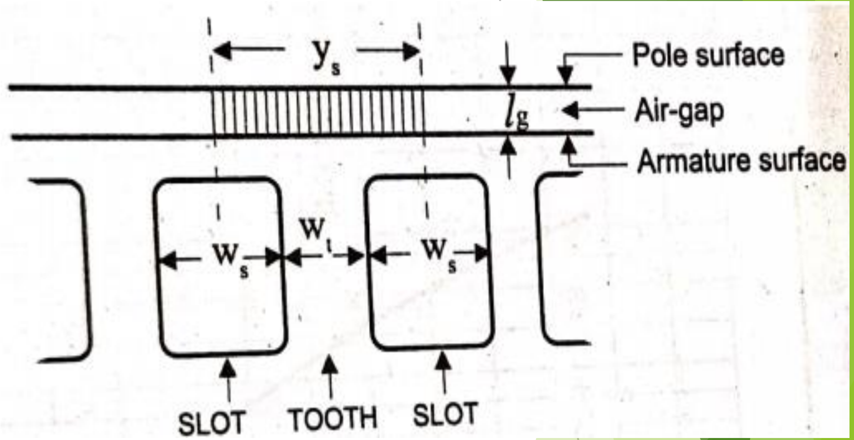
w_t - width of tooth

- Reluctance of a magnetic path , $\mathbf{S} = \frac{l}{\mu A}$

  l – length of magnetic path

  μ - permeability of the medium

  A – area of cross section of the magnetic path



- Consider the area of cross-section of the magnetic path over one slot of the armature

A= (length of the armature) *(slot pitch)

A= Ly_s

Reluctance of the air-gap, $S_g = \frac{l_g}{\mu_0 L y_s}$

where

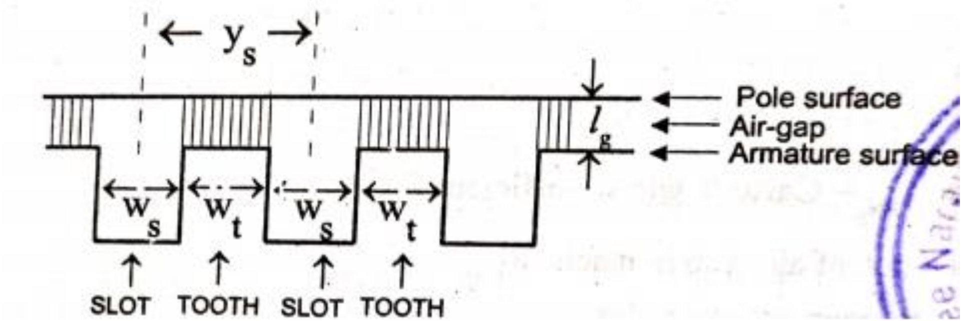
l_g- length of air-gap

μ_0- permeability of air

Ly_s- area of cross-section of air-gap over one slot

2) RELUCTANCE OF AIR-GAP IN MACHINES WITH OPEN ARMATURE SLOTS

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



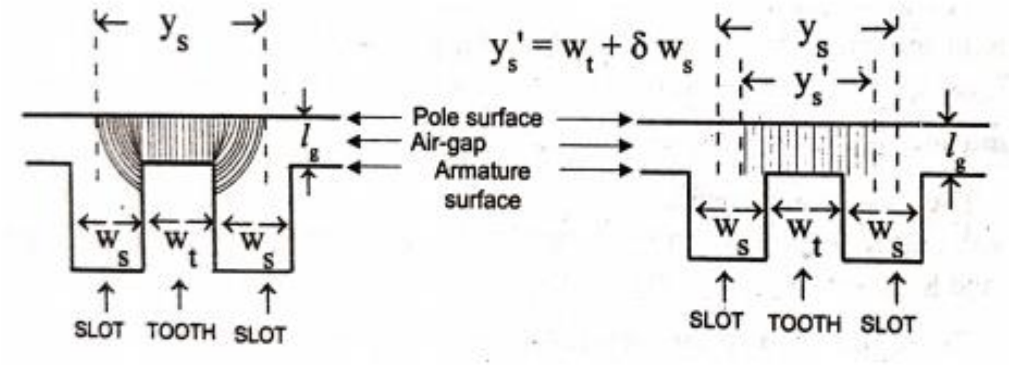
i) Reluctance of air-gap neglecting fringing effect

- Consider the armature with open type of slots
- The flux is only confined to the tooth width
- Area of cross-section of the air-gap through which the flux passes=L(y_s-w_s) =L w_t
- Reluctance of the magnetic path, S= $\frac{l}{\mu A}$
- **Reluctance of the air-gap in machines with open armature slots,**

$$S_g = \frac{l_g}{\mu_0 L(y_s - w_s)}$$

ii)Reluctance of air-gap including fringing effect

- In armatures with open slots the flux would fringe around the tooth
- Fringing increases the area of cross section of flux path
- Fringing of flux can be accounted by increasing the area of cross-section of flux path by δw_s



- Reluctance in this case is more than that of air-gap in smooth armature but is lesser than that of the case without including fringing effect
- Assume the flux is uniformly distributed over the whole of the slot pitch except for a fraction of slot width
- This fraction depends on the ratio of slot width to air-gap length
- Thus the flux of one slot is distributed over $w_t + \delta w_s$

- Effective slot pitch, $y_s' = w_t + \delta w_s$
- Add and subtract w_s

  $y_s' = w_t + w_s + \delta w_s - w_s$

  $= y_s + \delta w_s - w_s$

  $= y_s - (1-\delta) w_s$

  $= y_s - K_{cs} w_s$

  K_{cs}-Carter's gap coefficient for slots
- Reluctance of air-gap in machine with open armature slot,

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

- The gap contraction factor for slots K_{gs}

$$= \frac{Reluctance\ of\ air-gap\ in\ machine\ with\ open\ armature\ slot}{Reluctance\ of\ air-gap\ in\ machine\ with\ smooth\ armature}$$

$$= \frac{\frac{l_g}{\mu_0 L(y_s - K_{cs} w_s)}}{\frac{l_g}{\mu_0 L y_s}}$$

$$= \frac{y_s}{y_s - K_{cs} w_s}$$

- $\boldsymbol{K_{gs} = \frac{y_s}{y_s'}}$
- For semi-enclosed slots $w_s = w_0$, where w_0 - slot opening
- K_{gs} has a value greater than unity
- **The reluctance of air-gap in machine with open armature slot is K_{gs} times than that with smooth armature**

ESTIMATION OF CARTER'S GAP-COEFFICIENT FOR SLOTS

- The carter's gap-coefficient depends on the ratio of slot opening to gap length

$$K_{cs} = \frac{1}{1+5l_g/w_0}$$

- For parallel sided open slots,

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

- where, y= $\frac{w_0}{2l_g}$

MMF FOR AIR-GAP

- Non-magnetic materials have a constant value of permeability and so the B-H curve for them is a straight line passing through the origin
- mmf per meter of the path in non-magnetic material = $\frac{B}{\mu_0}$

$$= \frac{B}{4\pi 10^{-7}}$$

$$= 800{,}000 \text{ B in AT/m}$$

- B- Flux density in the non-magnetic material
- μ_0- Permeability of non-magnetic material

MMF FOR AIR-GAP IN ROTATING MACHINES

- The iron surfaces around air-gap are not smooth . The non-uniform air-gaps are due to the following:
  - *In machines with open or semi-enclosed slots, the flux concentrates on teeth i.e. the flux is not uniformly distributed in the air-gap.*
  - *Because of the radial ventilating ducts, there will be contraction of flux in axial direction*
  - *In salient pole machines, the air-gap dimensions are not constant over whole of the pole-pitch*

MMF OF AIR-GAP IN MACHINES WITH SMOOTH ARMATURE

- The mmf per metre for air-gap, $\boldsymbol{at_g} = \frac{B_{av}}{\mu}$

$$= \frac{B_{av}}{4\pi 10^{-7}}$$

$$= 800{,}000\ B_{av}$$

- **MMF required for air-gap of length l_g in machine with smooth armature ,**

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

MMF OF AIR-GAP IN MACHINE WITH OPEN ARMATURE SLOT AND RADIAL VENTILATING DUCTS

- MMF required for air-gap having a length l_g, in machines with slotted armature,

$$AT_g = K_g \text{x MMF required for air-gap of Length } l_g \text{ with smooth armature}$$

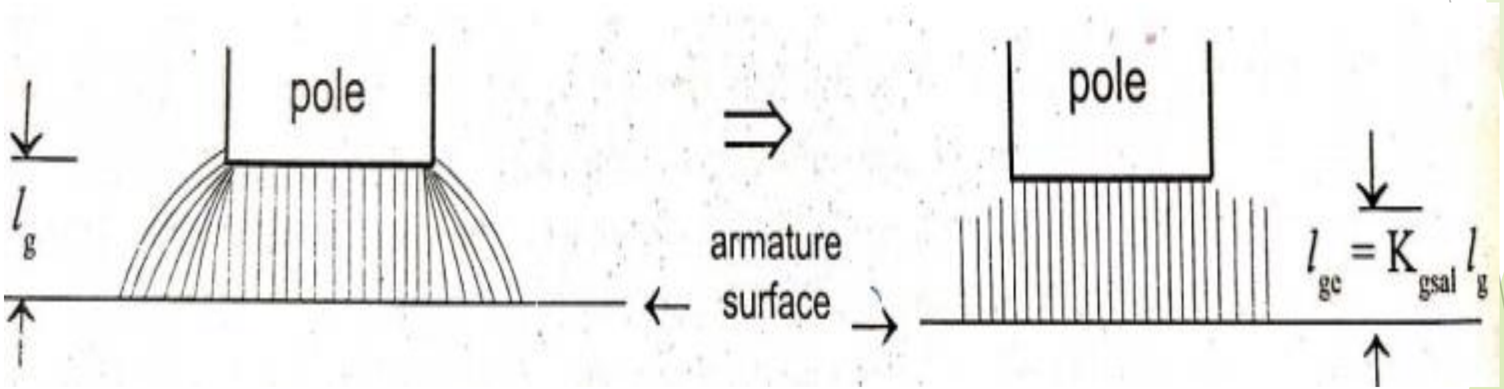
$$= K_g \text{x } 800{,}000\ B_{av}\ l_g$$

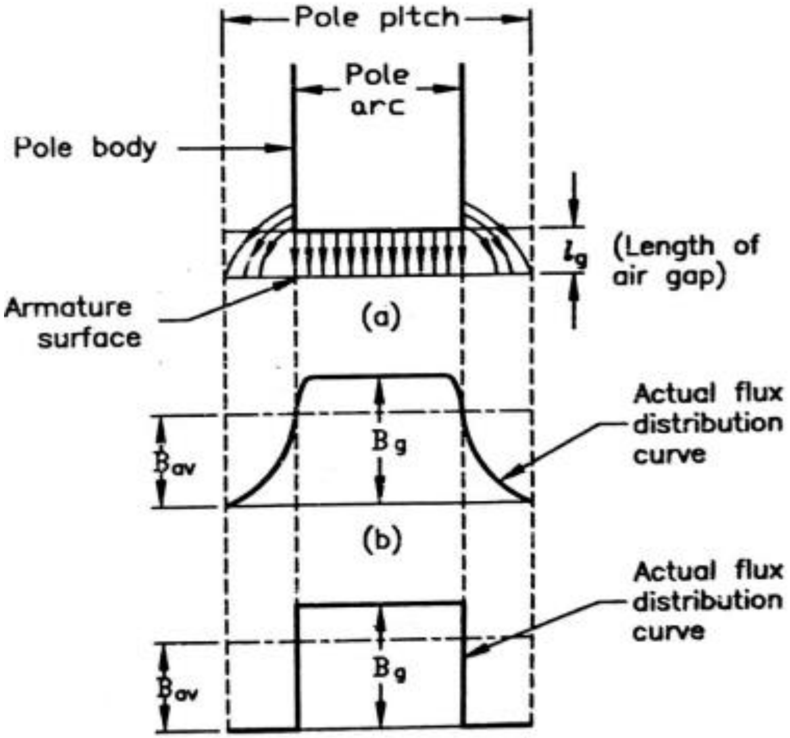
$$= 800{,}000\ B_{av}\ K_g\ l_g$$

- where, K_g - gap contraction factor

EFFECT OF SALIENCY ON THE MMF OF AIR-GAP

- In case of salient pole machines, the length of the air-gap is not constant over the whole pole pitch.
- To find mmf in this case , we can consider the length of air-gap as an effective gap given by $K_{gsal}\ l_g$
- K_{gsal}-gap contraction factor for salient poles
- For calculating AT_g in salient pole machines, the maximum gap density B_g at the centre of the pole is considered instead of average gap density


pole
l_g
armature
surface
pole
$l_{ge} = K_{gsal}\, l_g$


Pole pitch
Pole arc
Pole body
l_g (Length of air gap)
Armature surface
(a)
Actual flux distribution curve
B_{av}
B_g
(b)
Actual flux distribution curve
B_{av}
B_g

- MMF of air-gap in salient pole machines(dc/ac machines)

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

- where, K_g - total gap contraction factor including the effect of saliency

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

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

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

- $K_f = \Psi = \frac{Pole\ arc}{Pole\ pitch}$
- $K_f = \frac{B_{av}}{B_g}$
- $B_g = \frac{B_{av}}{K_f} = \frac{B_{av}}{\Psi}$

EFFECT OF VENTILATING DUCTS ON RELUCTANCE OF AIR-GAP

- When the length of the armature is higher than the diameter or when the length is greater than 0.1 m, **radial ventilating ducts** are used
- Radial ventilating ducts are small gaps of width w_d in between the stacks of armature core
- The core is normally divided into stacks of 40 to 80mm thick , with ventilating ducts of width 10 mm in between two stacks.
- Provision of radial ventilating ducts results in contraction of flux in axial direction
- Due to this effective axial length of the machine is reduced
- This results in an increase in the reluctance of air-gap.

- Treat stacks of laminations as teeth and the ducts as slots.
- Contracted or effective axial length, L’ = L- $K_{cd}n_d w_d$

  K_{cd} - Carter’s coefficient for ducts

  n_d - number of ducts

  w_d - width of the duct
- From empirical formula, $K_{cd} = \frac{1}{1+5l_g/w_d}$
- Gap contraction factor for ducts, $K_{gd} = \frac{\frac{l_g}{\mu_0 L' y_s}}{\frac{l_g}{\mu_0 L y_s}} = \frac{L}{L'}$

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

TOTAL GAP CONTRACTION FACTOR

- Reluctance of air-gap in machines with smooth armature without ducts = $\frac{l_g}{\mu_0 L y_s}$
- Reluctance of air-gap in machines with open armature slots and ducts = $\frac{l_g}{\mu_0 L y_s'}$
- **Total gap contraction factor,** K_g is defined as the ratio of reluctance of air-gap in machines with slotted armature and ducts to the reluctance of air-gap in machines with smooth armature and without ducts.

- $K_g = \dfrac{\dfrac{l_g}{\mu_0 L' y_{s'}}}{\dfrac{l_g}{\mu_0 L y_s}}$

$$= \frac{y_s}{y_{s'}} \frac{L}{L'}$$

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

GAP CONTRACTION FACTOR OF INDUCTION MOTOR

- In induction motor both stator and rotor has slots
- Total gap contraction factor for slots, K_{gs}=$K_{gss}K_{gsr}$
  - K_{gss}-gap contraction factor for stator slots
  - K_{gsr} -gap contraction factor for rotor slots
- Carter's coefficient for stator slots, K_{css}= $\frac{1}{1+5l_g/w_{0s}}$
- Carter's coefficient for stator slots, K_{csr}= $\frac{1}{1+5l_g/w_{0r}}$

- Gap contraction factor for stator slots, $\boldsymbol{K_{gss}} = \dfrac{y_{ss}}{y_{ss} - K_{css}w_{os}}$
- Gap contraction factor for stator slots, $\boldsymbol{K_{gsr}} = \dfrac{y_{sr}}{y_{sr} - K_{csr}w_{or}}$

  y_{ss}-stator slot pitch

  y_{sr}- rotor slot pitch

  w_{os}- stator slot opening

  w_{or}- rotor slot opening

- $y_{ss}=\dfrac{D}{S_s}$
- $y_{sr}=\dfrac{D-2l_g}{S_r}$

  D-Stator inner diameter

  S_s- number of stator slots

  S_r – number of rotor slots

ACTIVE IRON LENGTH

- The cores of magnetic circuits are built up with laminated steel plates wherever required
- These laminations are insulated from each other
- In order to have an effective cooling of the machine , the length of the core is divided into packets of about 40 to 80 mm width separated by vent spacers
- Vent spacers form ventilating ducts through which air is circulated
- These ducts are radial and their width normally varies from 8 to 10 mm
- Hence the whole length is not occupied by iron
- Some part is taken up by ventilating ducts and some part by insulation between steel laminations and air spaces created by irregularities in thickness of laminations.

Contd…

- Stacking factor, $K_i = \frac{Actual\ length\ of\ iron\ in\ a\ stack\ of\ assemmbled\ core\ plates}{Total\ axial\ length\ of\ stack}$
- K_i depends on thickness of plates and the type of insulating material employed
- Manufactures specify the stacking factor for a single lamination
- K_i-Average value of 0.9 may be assumed for all practical purposes
- Gross iron length, L_s = Length of slot portion conductor

  = core length- length of ventilating ducts

  =L - $n_d W_d$
- Net iron length, L_i= K_i(L - $n_d W_d$)

MMF FOR TEETH

- Calculation of mmf necessary to maintain the flux in the teeth is difficult due to the following problems:

  1. The teeth are wedge-shaped or tapered. This means that the area presented to the path of flux is not constant and this gives different values of flux density over the length of teeth.

  2. The slot provides another parallel path for the flux, shunting the tooth. The teeth are normally worked in the saturation region and therefore their permeability is low and as result an appreciable portion of the flux goes down the depth of the slots. The presence of two parallel paths and the reluctance of one part depending upon the degree of saturation in the other, makes the problem intricate

- The mmf required for teeth can be easily calculated whatever maybe their shape , if the flux going down is neglected. The correction to take slot flux into account can be incorporated later on.

Methods for the calculation of mmf required for teeth:

1. Graphical method
2. Three ordinate method(Simpson's method)
3. $B_{t1/3}$method

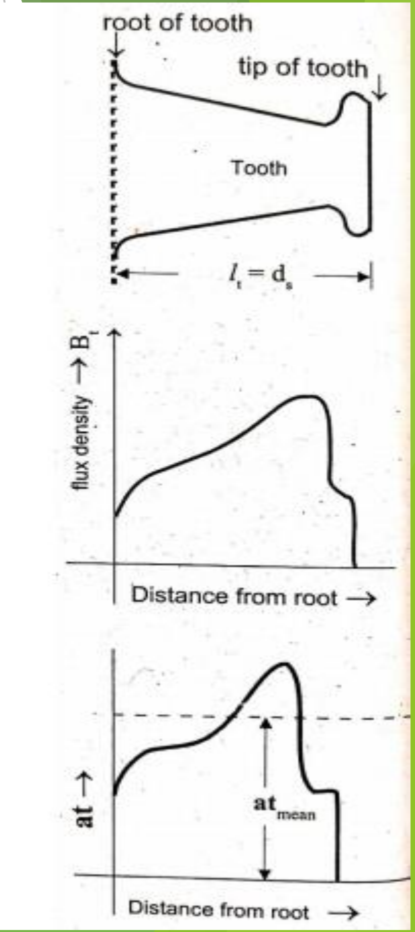
Graphical method

- First the **flux density at various sections** of the tooth are **determined**
- Flux density at any section of a tooth can be estimated by
- $B_t = \frac{\Phi}{n_t A_t}$

  Where, Φ- flux per pole

  n_t- number of teeth under a pole

  A_t- area of cross section of tooth at the desired section
- A **graph between flux density and distance from the tooth** is drawn
- Then **for each point of tooth the mmf per metre , at** (or H) is **found from** the knowledge of **B-at curve**
- A **graph between at and distance** is drawn. This **graph shows the variation of at over the length of the tooth**



- The mean ordinate of this graph gives the equivalent " ***at*** " for the whole of the tooth
- The mean ordinate is given by at_{mean} and is given by

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

- Total mmf required for the tooth

$$AT_t = at_{mean} * l_t = at_{mean} * d_s$$

- l_t=d_s

where l_t-Height of tooth

d_s-Depth of slot

Three ordinate method(Simpson's method)

- This method can be applied to teeth of very simple form and of a small taper
- Assumption: curve relating **at**(mmf per metre) with flux density is a parabola
- Flux density and the corresponding values of mmf per metre (at) are obtained at 3 equidistant points
- Three points chosen are: root, centre and tip of a tooth
- Flux density at these 3 points are estimated by, $B_t = \frac{\Phi}{n_t A_t}$
- Corresponding **at** are determined from B-**at** curve

- $\boldsymbol{at_1}$- **at** for the root of the tooth
- $\boldsymbol{at_2}$- **at** for the centre of the tooth
- $\boldsymbol{at_3}$- **at** for the tip of the tooth
- The mean value of **at** is given by, $\boldsymbol{at}_{mean}=\frac{\boldsymbol{at_1}+4\boldsymbol{at_2}+\boldsymbol{at_3}}{6}$
- The mmf required for the tooth, $AT_t = \boldsymbol{at}_{mean} l_t = \boldsymbol{at}_{mean} d_s$

where l_t-Height of tooth

d_s-Depth of slot

$B_{t1/3}$method

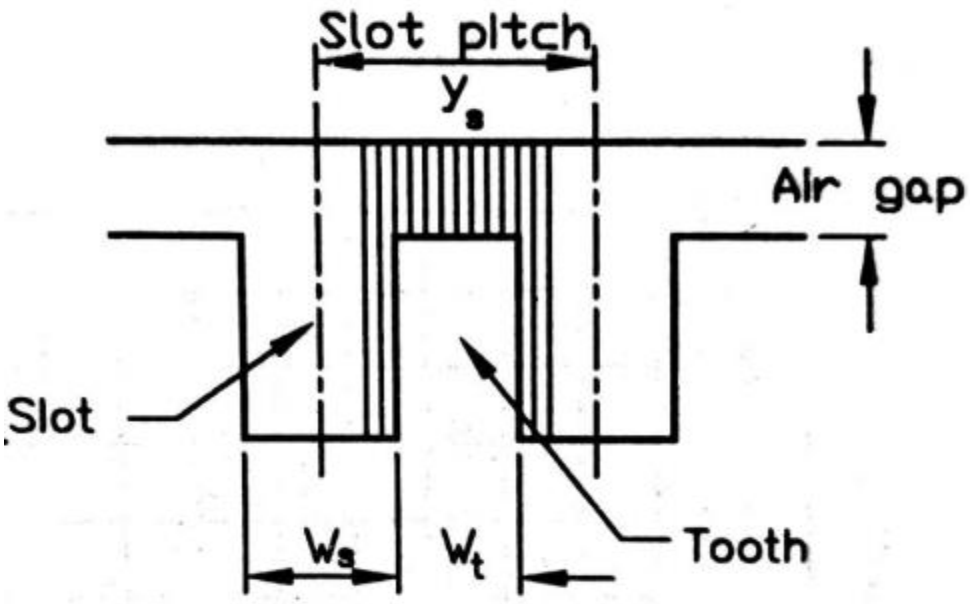
- This method is applied to teeth of small taper.
- Simple method
- This method is based on the assumption that value of mmf per metre, **at** obtained for flux density at a section one-third of tooth height from the narrow end is the $\boldsymbol{at}_{mean}$
- First calculate the flux density at one-third height from the narrow end by $\boldsymbol{B_t} = \frac{\Phi}{\boldsymbol{n_t A_t}}$
- From B-at curve ,find the value of **at** for this flux density. Let this **at** be denoted as $\boldsymbol{at}_{1/3}$
- Total mmf for tooth, $\boldsymbol{AT}_t = \boldsymbol{at}_{1/3} l_t = \boldsymbol{at}_{1/3} d_s$

where l_t-Height of tooth

d_s-Depth of slot

REAL AND APPARENT FLUX DENSITIES

- The flux entering an armature from the air-gap flows in teeth.
- Since the slots are in parallel with teeth, this mmf will act on the slots also.
- Thus some of the fluxes pass through slots.
- At higher flux densities the flux passing through the slots becomes large and cannot be neglected
- Hence the real flux passing through the teeth is always less than the total or apparent flux.
- Real flux density is always less than the apparent flux density


Slot pitch
y_s
Air gap
Slot
Tooth
W_s
W_t

Contd…

- Apparent flux density, $B_{app} = \frac{Total\ flux\ in\ a\ slot\ pitch}{Tooth\ area}$
- Real flux density, $B_{real} = \frac{Actual\ flux\ in\ a\ tooth}{Tooth\ area}$
- In an actual machine, there are two parallel paths for the flux over one slot pitch
  - Iron Path

    Area of iron path, A_i = Tooth width x net iron length = w_t x L_i
  - Air Path

    Area of air path, A_a= Total area-Iron area

    = (slot pitch * core length) –(tooth width* net iron length)

    = (y_sL)- ($w_t L_i$)

Contd…

- If Φ_s is the flux over one slot pitch ,then $\Phi_s = \Phi_i + \Phi_a$

  $where,$ Φ_i - flux passing through iron over a slot pitch

  Φ_a - flux passing through air over a slot pitch
- $K = \frac{A_a}{A_i} = \frac{Air\ area}{Iron\ area}$
- $B_a = \mu_0 H$

  $= 4\pi 10^{-7} H$

  $= 4\pi 10^{-7} at_{real}$
- Apparent flux density, $B_{app} = \frac{Total\ flux\ over\ a\ slot\ pitch}{Iron\ area\ over\ a\ slot\ pitch} = \frac{\Phi_s}{A_i}$

  $= \frac{\Phi_i + \Phi_a}{A_i} = \frac{\Phi_i}{A_i} + \frac{\Phi_a}{A_i} = B_{real} + \frac{\Phi_a}{A_i} = B_{real} + \frac{\Phi_a}{A_a}\frac{A_a}{A_i}$

  $= B_{real} + B_a \frac{A_a}{A_i}$

  $= B_{real} + B_a K$

Contd…

- B_{app} = B_{real} +$B_a K$
- B_{real} = B_{app}- $4\pi 10^{-7} at_{real}$K
- B_{real} = B_{app}- $4\pi 10^{-7} at_{real}(K_s$ -1)
- K_s = 1+ K =$\frac{Total\ area}{Iron\ area}$ = $\frac{Ly_s}{L_i w_t}$

MODULE 1

Principles of electrical machine design - General design considerations - specifications of machines - types of enclosures - types of ventilation - heating - short time rating - overload capacity - temperature rise time curve - hot spot rating.

Magnetic circuit calculation - calculation of field ampere turns - air gap mmf - effect of slot and ventilating duct - active iron length - mmf for teeth - real and apparent flux densities - mmf per pole. Magnetic Leakage Calculation- Effects of Leakage. Armature Leakage – Components. Unbalanced Magnetic Pull-Practical aspects of unbalanced magnetic pull

MAGNETIC LEAKAGE

- It is impossible to confine all the flux to useful paths, there being always a leakage flux
- Leakage Flux: The flux which passes through unwanted path
- Leakage flux does not contribute to either transfer or conversion of energy
- Leakage coefficient, $C_l = \frac{Total\ flux}{Useful\ flux} = \frac{Useful\ flux + Leakage\ flux}{Useful\ flux}$

EFFECTS OF LEAKAGE FLUX

- If the **leakage flux alternates**, it will **induce voltage** in any **winding** with **which it links**. This is known as **leakage reactance voltage**. The reactance corresponding to this voltage **plays an important role** in the **performance of ac machines**.
- In **DC machines**
  - **Leakage flux** passing through the non-useful path **affects the field excitation** of the machines
  - The **excitation** has to be **increased to compensate** for the **loss of flux**
  - **During commutation** when the coil currents are reversed the leakage flux is also reversed , giving **rise to reactance voltage**
  - This **reactance opposes** the **change in current** and makes the **commutation difficult**

EFFECTS OF LEAKAGE FLUX

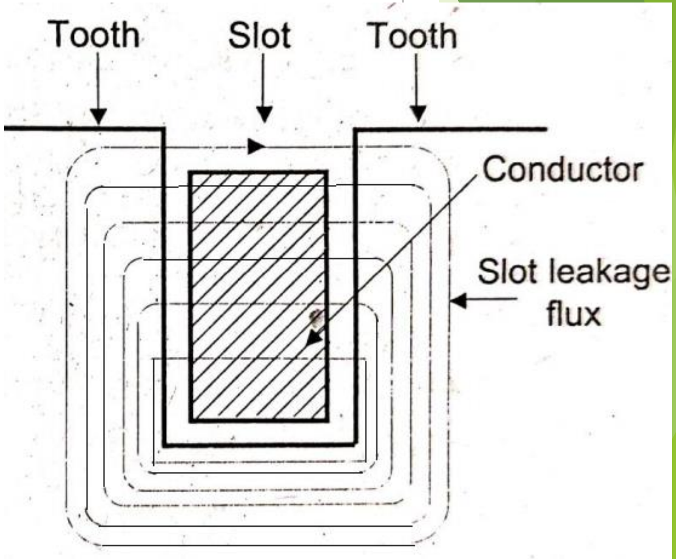
- The leakage flux affects the following performance indices of various machines:
  - **Excitation demand of salient pole machines**
  - **Performance of ac machines depends on the leakage reactance**
  - **Forces between the windings under short circuit condition**
  - **Voltage regulation of generators and transformers**
  - **Commutation conditions in DC machines**
  - **Stray load losses**
  - **Circulating currents in transformer tank walls**

TYPES OF LEAKAGE FLUX

- Different types of armature leakage fluxes are:
  - **Slot leakage flux**
  - **Tooth top leakage flux**
  - **Zigzag leakage flux**
  - **Overhang leakage flux**
  - **Harmonic or Differential leakage flux**
  - **Skew leakage flux**
  - **Peripheral leakage flux**

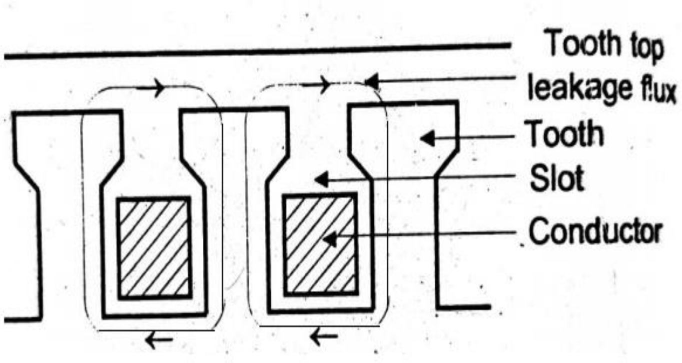
SLOT LEAKAGE FLUX

- The **fluxes** that **crosses the slot from one tooth to the next** and returning through iron are **called slot leakage flux**
- They link the conductors below them
- The slot leakage **depend on the shape of the slot**
- **Narrow Slot-Leakage flux large** (Semi enclosed Slots - Induction Machines)
- **Wide Slot-Leakage flux small** (Open Slots - DC and Synchronous Machines)



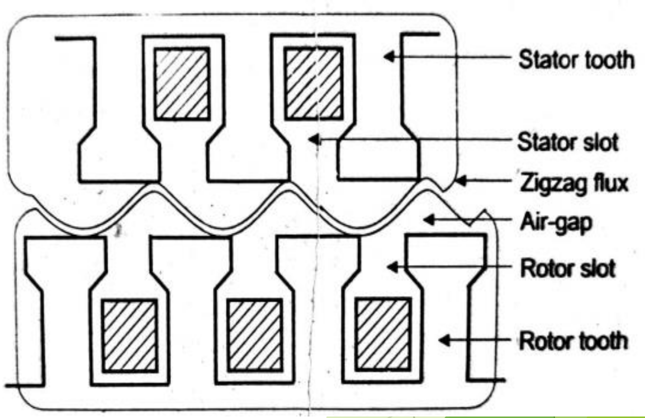
TOOTH TOP LEAKAGE FLUX

- The flux flowing from **top of one tooth to the top of another tooth** is called **tooth top leakage flux**
- This type of **flux** is considered only in machines with **large air-gap length** like **DC machines and synchronous machines**
- This type of flux is **negligible** in **induction machines**, as the **air-gap length** is **very small**



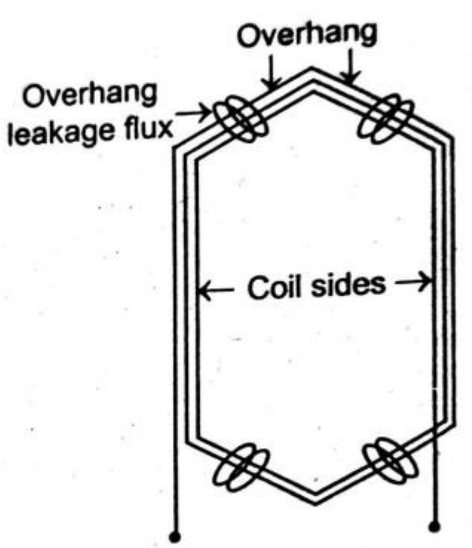
ZIGZAG LEAKAGE FLUX

- The **flux** passing **from one tooth to another** in a **zigzag fashion** across the air-gap is called **zigzag leakage flux**
- The **magnitude** of this flux **depends** upon the **length of air-gap and relative position** of the tips of **stator and rotor teeth**
- Found in **wound rotor Induction Machines** where **flux** takes **path** between **stator teeth and rotor teeth**



OVERHANG LEAKAGE FLUX

- The **end connections** (the conductor which connects the two sides of a coil) are **called Overhang**
- The **fluxes** produced **by** the **overhang portion** of the armature winding are called **Overhang leakage flux**
- It **depends** on the **arrangement of** the **overhang**
- Mainly its **path through the air** but **sometimes** part of it through the **iron core**
- **Absent** in **Induction Machines** (No Overhang)



HARMONIC / DIFFERENTIAL/ BELT LEAKAGE FLUX

- These **fluxes** are due to the **dissimilar mmf distribution** in **stator and rotor**
- The primary and secondary mmf distribution are not similar
- In **squirrel cage induction motor** the rotor current is exactly balanced by stator current and so there is **no harmonic leakage flux**

SKEW LEAKAGE FLUX

- This is only **present when** the **slots are skewed**
- **Skewing** is done only in **squirrel cage induction motors** to eliminate harmonic torques and noise
- If the **rotor slots** are **skewed**, the **voltage** in **rotor conductors** is **reduced**
- This **results in reduction of mutual flux** causing a **large difference between total flux and mutual flux**
- This **difference** is **accounted** as **skew leakage flux**

PERIPHERAL LEAKAGE FLUX

- The **fluxes flowing circumferentially round the air-gap** without linking with any of the windings are called **peripheral leakage flux**
- This **flux is negligible in most** of the **machines**

UNBALANCED MAGNETIC PULL

- In rotating machines if the air-gap around the armature periphery is non-uniform then radial forces are developed in the rotor
- The radial forces will act perpendicular to rotor axis
- This force or pull is called the unbalanced magnetic pull

Let an electromagnet be arranged as in fig.

If one of the pole is moved by a distance, dx

→ Workdone = force x Distance = $f \cdot dx$

→ Change in energy = Energy density x Change in volume

$$= \frac{1}{2}\frac{B^2}{\mu_0} \times A\,dx$$

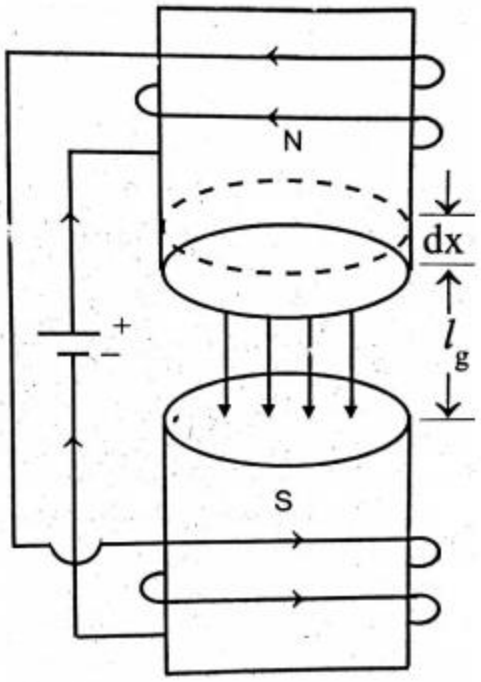
Workdone = Change in energy

$$f\,dx = \frac{1}{2}\frac{B^2}{\mu_0} A\,dx$$

$$\boxed{f = \frac{1}{2}\frac{B^2 A}{\mu_0}} \; N$$

force or pull per unit area

$$\boxed{P_m = \frac{1}{2}\frac{B^2}{\mu_0}} \; N/m^2$$



flux density in the air-gap, B, depends upon the mmf of the exciting winding.

Total mmf, $AT = AT_g + AT_i$

flux density, $B = \frac{\mu_0 AT_g}{l_g}$

$$f = \frac{1}{2}\left[\frac{\mu_0 AT_g}{l_g}\right]^2 \frac{A}{\mu_0}$$

$$= \frac{1}{2}\mu_0\left[\frac{AT_g}{l_g}\right]^2 A$$

If iron parts are not saturated, then AT_i is negligible

$\therefore AT = AT_g$

If saturation of iron part are not neglected

$$f = \frac{1}{2}\mu_0\left[\frac{AT}{l_g}\right]^2 A$$

Consider an ideal 2 pole machine.
Rotor is set symmetrically with stator.
Rotor is concentric with stator

- Force of attraction between top stator and rotor poles

$$f_1 = \frac{1}{2}\frac{B^2}{\mu_0}A = \frac{1}{2}\mu_0\left(\frac{AT_g}{l_g}\right)^2 A$$

$$f_1 = \frac{1}{2}\mu_0\left(\frac{AT}{l_g}\right)^2 A$$

If mmf required for iron part is negligible.

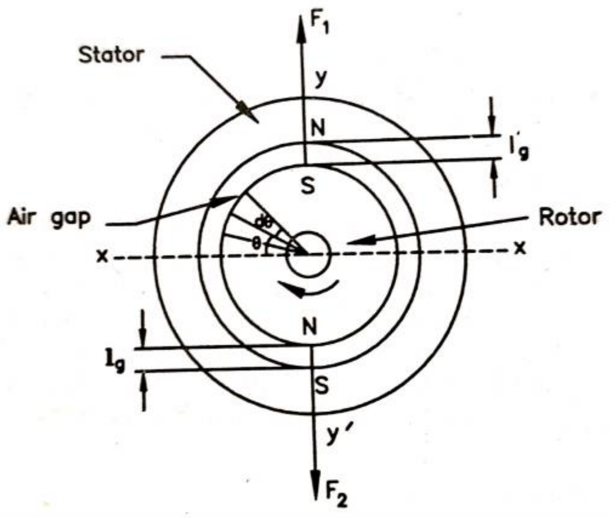
- Force of attraction between the ~~no~~ bottom stator & rotor poles.

$$f_2 = \frac{1}{2}\frac{B^2}{\mu_0}A$$

$$f_2 = \frac{1}{2}\mu_0\left(\frac{AT}{l_g}\right)^2 A$$

$$f_1 = f_2$$

Forces f_1 and f_2 are equal and act in opposite direction
Hence resultant is equal to zero.
In symmetrical machine there is no radial magnetic pull on the rotor.



→ Force of attraction between top stator and rotor poles.

$$F_1 = \frac{1}{2}\frac{B_1^2}{\mu_0}A$$

$$= \frac{1}{2}\left[\frac{\mu_0 AT}{l_{g_1}}\right]^2 \frac{A}{\mu_0}$$

$$= \frac{1}{2}\mu_0\left(\frac{AT}{l_{g_1}}\right)^2 A$$

→ Force of attraction between bottom stator and rotor poles

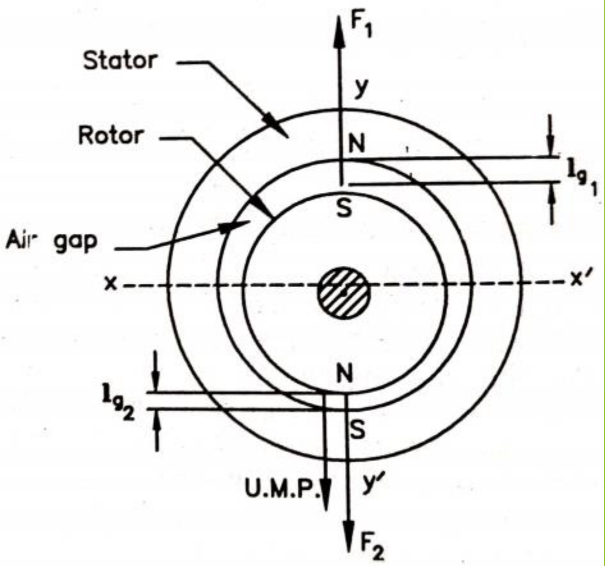
$$F_2 = \frac{1}{2}\frac{B_2^2}{\mu_0}A$$

$$= \frac{1}{2}\mu_0\left(\frac{AT}{l_{g_2}}\right)^2 A$$

$$l_{g_1} > l_{g_2} \Rightarrow F_2 > F_1$$

A radial force (pull) acts on rotor in the downward direction

This force or pull is called the Unbalanced Magnetic Pull.



ESTIMATION OF UNBALANCED MAGNETIC PULL

In ac machines, B represents the rms value of flux density. If the flux distribution is sinusoidal and B_m is the maximum value of flux density then rms value of flux density is $B_m/\sqrt{2}$.

The unbalanced magnetic pull in dc and ac machines can be estimated from the following formulae.

Let e = Displacement of rotor (or eccentricity of rotor)

Magnetic pull per unit area, $P_m = \frac{1}{2} \frac{B^2}{\mu_0}$

Area per pole, $A = \frac{\pi D L}{P}$

→ Unbalanced magnetic pull due to pair of poles

$$P_p = 2 A \cdot P_m \frac{e}{l_g}$$

→ Unbalanced magnetic pull due to p no. of poles

$$UMP = \text{Pole pair} \times P_p$$

$$= \frac{P}{2} \times 2AP_m \frac{e}{l_g}$$

$$= pAP_m \frac{e}{l_g}$$

When the poles are located at an angle θ with horizontal axis

→ Unbalanced magnetic pull acting downwards due to a pair of poles

$$= 4 AP_m \frac{e}{l_g} \sin^2\theta$$

PRACTICAL ASPECTS OF UNBALANCED MAGNETIC PULL

- Some of the practical aspects of UMP that must be taken into account while designing electrical machines are:

i) Unbalanced magnetic pull is very large especially in induction motors

- A small eccentricity can cause a fairly large UMP as the length of the air-gap in IM is very small. Small air-gap length is provided to get best operating condition and to get best pf.
- In order to maintain uniformity of air-gap in IM, the following aspects are incorporated:

a. Ball bearings are used so that a good alignment can be maintained over a long period. The use of ball bearings prevents wear and also reduces noise

b. Stator windings of IMs are designed with parallel paths having equalizer connections. These helps in overcoming the effects of the unbalance.

c. A stiff and short shaft gives negligible eccentricity and therefore the UMP is small

Contd…

ii) Certain slot combinations of stator and rotor slots have a strong tendency to produce noise and vibrations.

- The slots on both rotor and stator produce harmonic fields.
- If two harmonic fields, with number of poles differing by two, co-exist in the air-gap of an induction motor, they produce UMP and consequent radial vibration of rotor as a whole.
- Due to different pole numbers, symmetrical radial forces of high frequencies are produced. These creates stator vibrations and magnetic noise

Contd…

iii) There is considerable homopolar flux provided in 2 pole machines due to asymmetry in the air-gap.

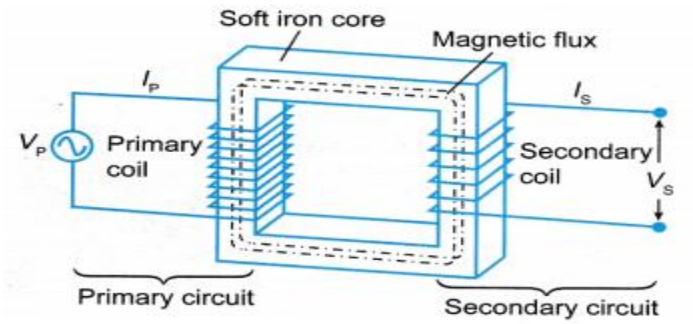
- The flux path is completed through shaft and frame
- There is modulation of the air-gap length which induces an emf in the bars of squirrel cage windings of IMs
- This effect may be counteracted by use of parallel paths and equalizer connections in the stator windings.

MODULE 2

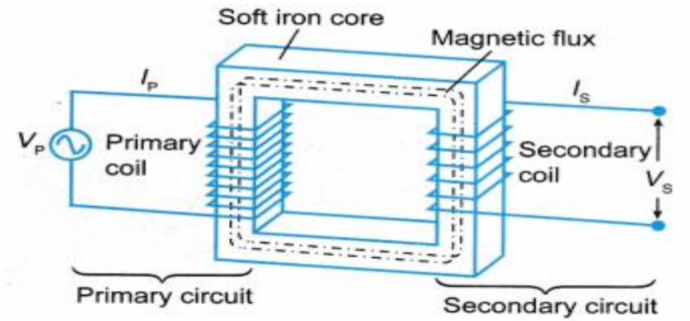
Design of transformers - single phase and three phase transformers - distribution and power transformers - output equation - core design - window area - window space factor - overall dimensions of core. Windings – no. of turns - current density - conductor section - Cooling of transformers

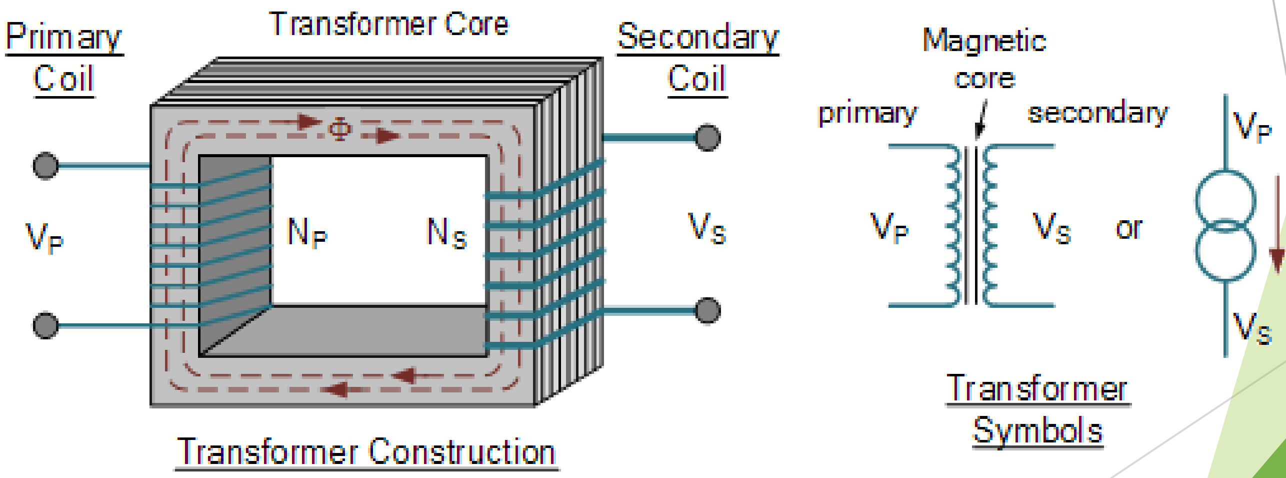
DESIGN OF TRANSFORMER

- Transformer is a **Static device**
- **Primary** is connected to the ac voltage source
- **Secondary** winding is connected to the load
- Consists of laminated core



- An alternating flux is produced ,whose amplitude depends on the primary voltage and number of turns
- Primary induced voltage, E_p= 4.44 f$\Phi_m T_p$
- The flux linking with the secondary winding induces an emf that depends on the amplitude of the flux and number of secondary turns
- E_s= 4.44 f$\Phi_m T_s$
- $\frac{E_s}{E_p} = \frac{T_s}{T_p}$ = K

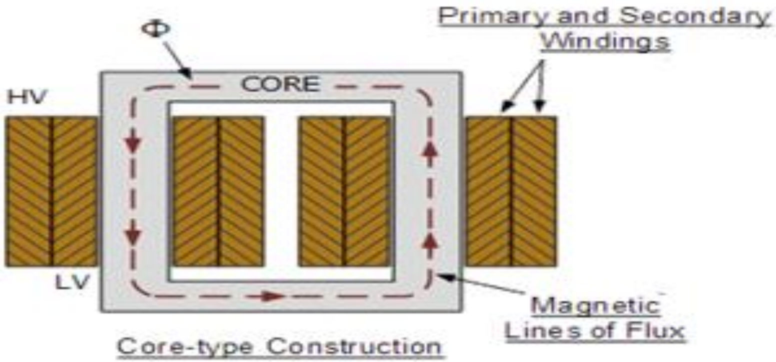




Primary Coil
Transformer Core
Secondary Coil
Φ
VP
NP
NS
VS
Transformer Construction
Magnetic core
primary
secondary
VP
VS
or
VP
VS
Transformer Symbols

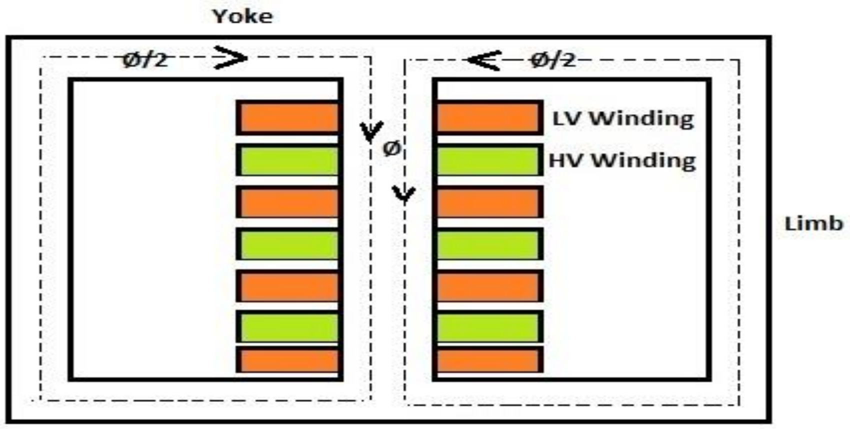
SINGLE PHASE TRANSFORMER

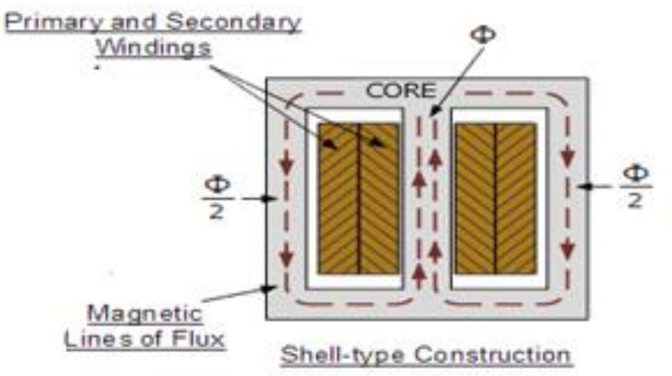
- <u>Single phase core type</u>
- Consists of two legged iron frame with one half of the primary winding and one half of the secondary winding wound on each leg
- The l.v and h.v windings are concentric with each other
- L.v winding is placed on the inner side nearer to the core
- Consists of one window

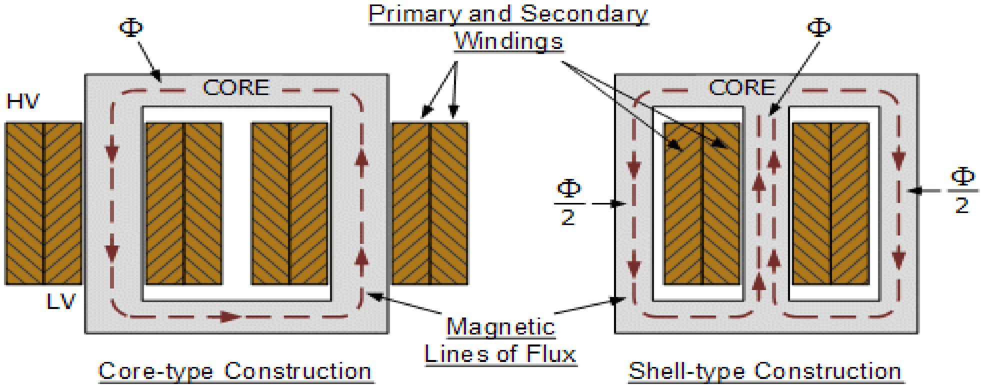


Single phase shell type

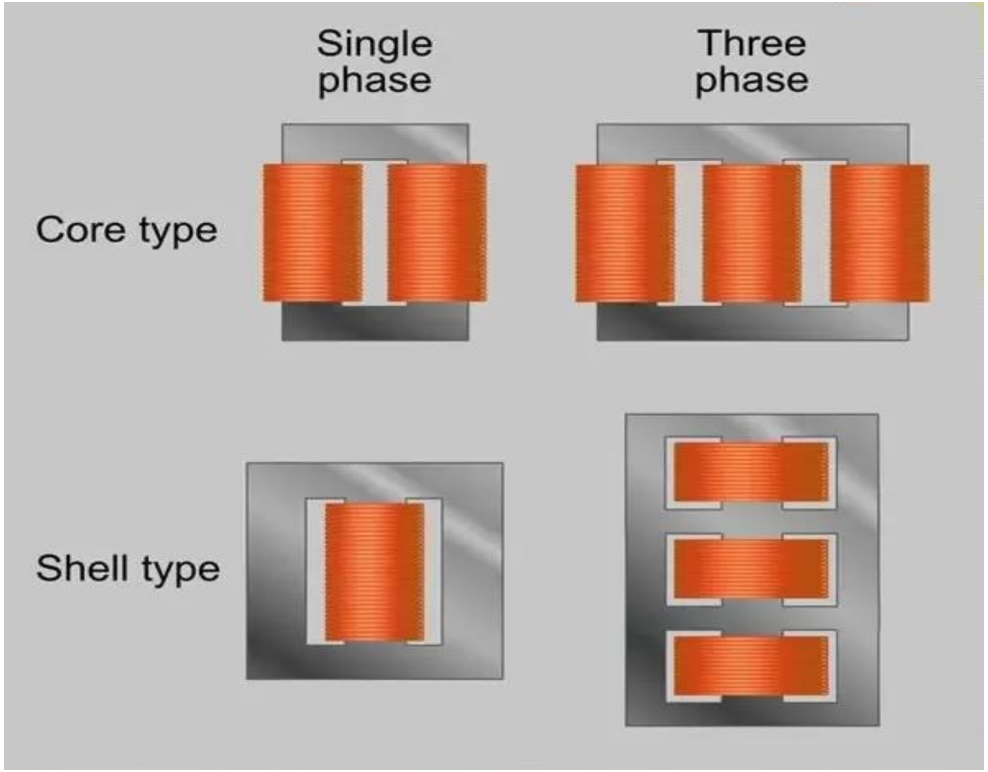
- The l.v and h.v coils are sandwiched between each other






Φ
HV
CORE
LV
Primary and Secondary Windings
Magnetic Lines of Flux
Φ
CORE
Φ/2
Φ/2
Core-type Construction
Shell-type Construction

CORE TYPE	SHELL TYPE
Winding encircles the core	Core encircles most part of the winding
Simpler in design	Complex design compared to core type
Permits easy assembly and insulation of windings Easy to dismantle for repair work	Assembly and dismantling is difficult
Cylindrical type of coils are used	Multilayer disc type or sandwich coils are used
As windings are distributed natural cooling is more effective	Natural cooling is not possible
Preferred for low voltage transformer	Preferred for high voltage transformer
It has single magnetic core	It has double magnetic core
In single phase type, core has two limbs	In single phase type, core has three limbs

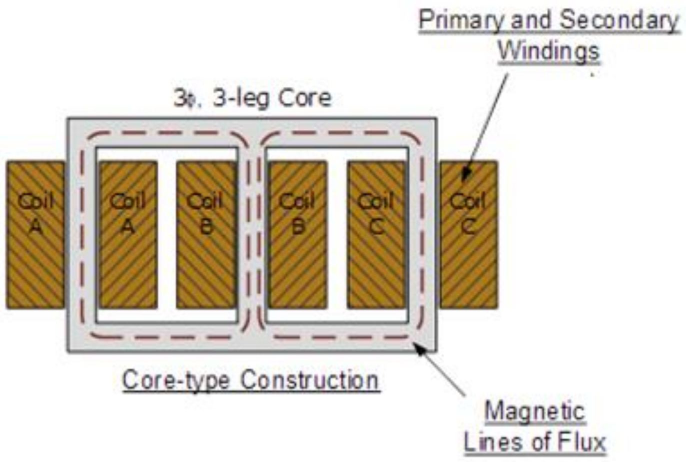

Single
phase
Three
phase
Core type
Shell type

THREE PHASE TRANSFORMER

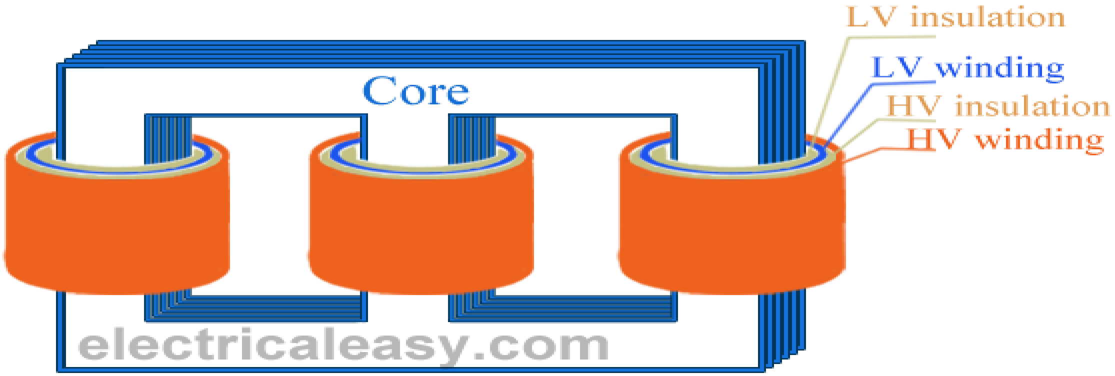
- A transformer bank used on three phase system consists of 3 independent 1-phase transformer
- Three phase transformation is also possible through one three phase transformer having a magnetic circuit common to all the three phases

THREE PHASE CORE TYPE

- The core consists of **three legs** with magnetic circuit completed through two yoke
- A primary and secondary windings of each phase are wound on each leg
- Flux flows up in one leg and flows down in other two legs
- Transformer has **two windows**
- Each of the window contains two primary and two secondary windings



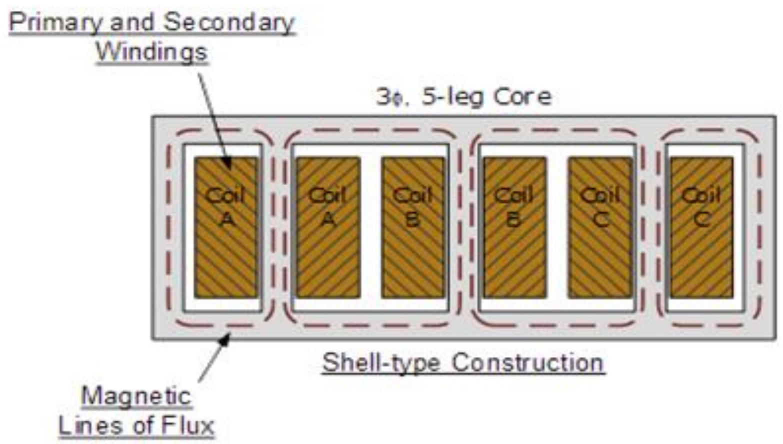
THREE PHASE TRANSFORMER

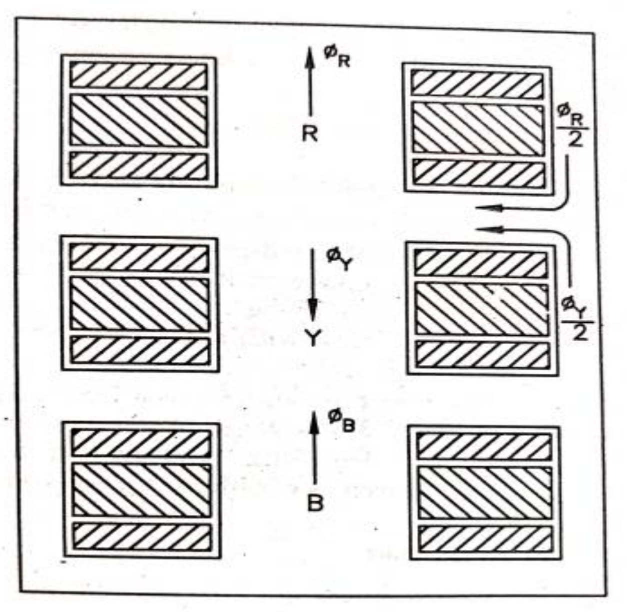


Core type three phase transformer

THREE PHASE SHELL TYPE

- The windings of the middle core are reversed so that the part of the core carry flux $\Phi_R/2$ + $\Phi_Y/2$ or $\Phi_Y/2$ + $\Phi_B/2$ instead of $\Phi_R/2$ - $\Phi_Y/2$ or $\Phi_Y/2$ - $\Phi_B/2$





Classifications of transformer

- Based on output voltage:
  - **Step-up transformer-** transformers which raise the voltage(Vs>Vp)
  - **Step-down transformer-** transformers which lower the voltage(Vs<Vp)
- Based on service:
  - **Distribution transformer**
  - **Power transformer**
- Based on core :
  - **Core type transformer**
  - **Shell type transformer**

DISTRIBUTION TRANSFORMER

- Transformers **upto 500kVA**, used to step-down the distribution voltage or from transmission voltage to distribution voltage
- They are **kept in operation all the 24 hours** a day whether they are carrying any load or not.
- Energy is lost in iron losses throughout the day while the copper losses account for the loss in energy when the transformer is loaded.
- Therefore iron losses should be small compared to copper losses
- Distribution transformers should be designed to have **maximum efficiency at a load much lower than full load**(about 50%)
- It has good all day efficiency
- **Good voltage regulation**
- **Small value of leakage reactance**

POWER TRANSFORMER

- They have rating **above 500kVA**
- Power rating of power transformer are in the order of MVA
- Used in **generating stations or substations**
- Used at the end of the power transmission line for stepping up or stepping down the voltage
- They are put in operation during load periods and are disconnected during light load periods
- It is designed to have **maximum efficiency at or near full load**.
- Voltage regulation is less
- **Greater leakage reactance** than distribution transformer

OUTPUT EQUATION OF SINGLE PHASE TRANSFORMER

Emf induced in transformer, $E = 4.44 f \phi_m T$

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

$$E_t = \frac{E_p}{T_p} = \frac{E_s}{T_s}$$

f - frequency, Hz
ϕ_m - Main flux, Wb
E_p, E_s - emf induced in 1° & 2°
T_p, T_s - No. of turns of 1° & 2°

→ Total copper area in window

A_c = Cu area of 1° + Cu area of 2°

= 1° turns × area of 1° conductor + 2° turns × area of 2° conductor

$= T_p a_p + T_s a_s$

Taking current density 'δ' same in both 1° & 2°

I_p, I_s - 1° & 2° current

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

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

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

$$\boxed{A_c = \frac{2AT}{\delta}} \qquad \text{——— (1)}$$

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

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

$$\boxed{A_c = K_w A_w} \qquad \text{——— (2)}$$

Equating (1) & (2)

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

$$AT = \frac{K_w A_w \delta}{2} \quad \text{--- (3)}$$

Rating of a single phase transformer in kVA

$$Q = V_p I_p \cdot 10^{-3} = E_p I_p \, 10^{-3} \qquad (V_p \approx E_p)$$

$$= E_t T_p I_p \cdot 10^{-3}$$

$$E_t = \frac{E_p}{T_p}$$

$$= E_t AT \cdot 10^{-3}$$

$$E_p = E_t T_p$$

$$= E_t \cdot \frac{K_w A_w \delta}{2} \cdot 10^{-3} \qquad [\text{Substituting eq. (3)}]$$

$$= 4.44 f \phi_m \frac{K_w A_w \delta}{2} \cdot 10^{-3} \qquad [\text{Subs. value for } E_t]$$

$$= 2.22 f \phi_m K_w A_w \delta \cdot 10^{-3}$$

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

A_i – Net core area

A_i = Stacking factor × Gross core area

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

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

OUTPUT EQUATION OF THREE PHASE TRANSFORMER

In case of 3φ transformers, each window contains two 1° & two 2° windings.

Emf induced in transformer, $E = 4.44 f \phi_m T$

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

$$E_t = \frac{E_p}{T_p} = \frac{E_s}{T_s}$$

Total conductor area in each window,

$A_c = 2$ (Cu area of 1° + Cu area of 2°)

$= 2$ (1° turns × area of 1° cond. + 2° turns × area of 2° cond.)

$$= 2(T_p a_p + T_s a_s) = 2\left(\frac{T_p I_p}{\delta} + \frac{T_s I_s}{\delta}\right) = 2\left[\frac{T_p I_p + T_s I_s}{\delta}\right]$$

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

$$\boxed{A_c = \frac{4AT}{\delta}} \quad \text{—— (1)}$$

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

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

$$\boxed{A_c = K_w A_w} \quad \text{—— (2)}$$

Equating (1) & (2)

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

$$\boxed{AT = \frac{K_w A_w \delta}{4}} \quad \text{—— (3)}$$

KVA Rating of 3ϕ transformer is given by

$$Q = 3 \cdot V_p I_p \cdot 10^{-3}$$

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

$$= 3 E_t T_p I_p \cdot 10^{-3}$$

$$= 3 E_t AT \cdot 10^{-3}$$

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

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

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

$E_t = \frac{E_p}{T_p}$

$E_p = E_t T_p$

Sub. eq. ③ and value for E_t

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

$\phi_m = B_m A_i$

A_i – Net core area

A_i = stacking factor × Gross core area

VOLT PER TURN (EMF PER TURN)

The transformer design starts with the selection of an appropriate value for emf per turn

Let, ratio of specific magnetic and electric loading $\left.\right\}$ $r = \frac{\phi_m}{AT}$

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

The volt-ampere per phase of a transformer is given by the product of voltage and current per phase. Considering the primary voltage and current per phase we can write,

$$\text{kVA per phase, } Q = V_p I_p \times 10^{-3}$$

$$= 4.44\, f \phi_m T_p I_p \times 10^{-3} \quad (\because V_p \approx E_p = 4.4 f \phi_m T_p)$$

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

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

$$E_t = \frac{E_P}{T_P}$$

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

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

We know that,

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

On substituting the value for ϕ_m

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

$$E_t = K\sqrt{Q}$$

where, $K = \sqrt{4.44\, f\, r \times 10^3} = \sqrt{4.44\, f \times \frac{\phi_m}{AT} \times 10^3}$

emf per turn directly proportional to K.

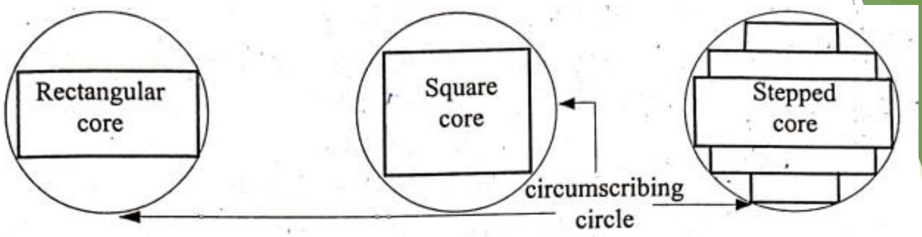
Q is the kVA rating of single phase transformer and Q is kVA per phase for three phase transformer

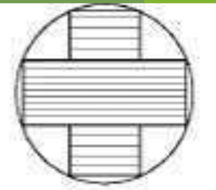
Transformer type	K
Single phase shell type	1.0 to 1.2
Single phase core type	0.75 to 0.85
Three phase shell type	1.3
Three phase core type, distribution transformer	0.45
Three phase core type, power transformer	0.6 to 0.7

TRANSFORMER CORE

- **Eddy current losses and hysterisis losses occur in core and yoke**
- To **minimize** eddy current **loss - Silicon steel laminations** are used
- **Laminations** are **insulated** from **each other by thin film varnish**
- Earlier **hot rolled steel** were being used working upto **flux density 1.4 Wb/m^2**
- **Cold rolled grain oriented** (CRGO) silicon steel works upto **1.7 Wb/m^2**
- By using **CRGO** the specific **losses are reduced** to approximately **50% than** that in **hot rolled steels**
- Generally **circular coils** are used **for HV and LV windings** of transformers
- **Circular coils** have **better mechanical strength than** that of **rectangular coils**
- Circumscribing Circle - Circle representing the inner surface of the tubular form carrying the windings

- Types of Cores
  - Rectangular Core
  - Square cores
  - Stepped Cores





(c) Cruciform

- For Core type transformer – square, rectangular or stepped core
- For Shell type transformer- rectangular core
- **Rectangular Core**
  - For core type distribution transformers and small power transformers(for moderate and low voltage)
- **Square cores**
  - **Used** for **small transformers** and also when circular coils are required for **high voltage distribution and power transformer**
  - **Diameter** of the **circumscribing circle** is **larger**, results in **mean length of** the transformer **turns is large**

- Require **large** amount of **copper**
- In case single square or rectangle core is being used **for large transformers**, the **utilization of space is not proper**

- **Stepped Core**
  - To **utilize** the **space** available and also to **minimize** the **mean length of** the transformer **turns**
  - **Diameter** of the **circumscribing circle** over the core will be **less**
  - Hence there is **savings in copper for windings**
  - However with **larger number of steps** a large number of **different sizes of laminations** have to be **used**
  - This results in **higher labour charges**

SQUARE CORE

Let d = diameter of circumscribing circle

Also, d = diagonal of the square core

a = side of square

Diameter of circumscribing circle, $d = \sqrt{a^2 + a^2} = \sqrt{2a^2} = \sqrt{2}\,a$

$\therefore$ Side of square, $a = d/\sqrt{2}$

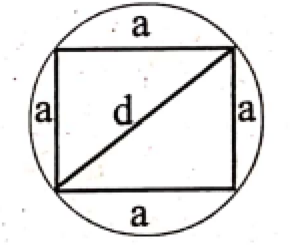
Gross core area, A_{gi} = area of square $= a^2 = (d/\sqrt{2})^2 = 0.5\,d^2$

Let stacking factor, $S_f = 0.9$

Net core area, A_i = Stacking factor × Gross core area

$= 0.9 \times 0.5\,d^2 = 0.45\,d^2$.

Area of circumscribing circle $= \frac{\pi}{4} d^2$



$$\text{The ratio, } \frac{\text{Net core area}}{\text{Area of circumscribing circle}} = \frac{0.45\, d^2}{(\pi/4)\, d^2} = 0.58$$

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

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

$$= \frac{A_i}{d^2} = \frac{0.45\, d^2}{d^2} = 0.45$$

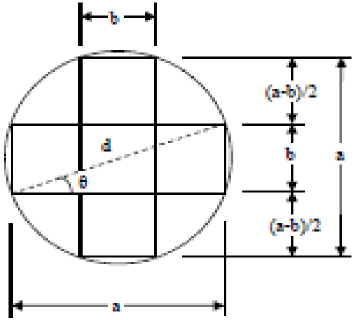
TWO STEPPED CORE (CRUCIFORM)

Let, a – Length of the rectangle

b – breadth of the rectangle

d – diameter of the circumscribing circle and diagonal of the rectangle.

θ – Angle b/w the diagonal and length of the rectangle.



- The max. core area for a given 'd' is obtained by the max value of 'θ'
- For max value of 'θ',

$$\frac{dA_{gi}}{d\theta} = 0$$

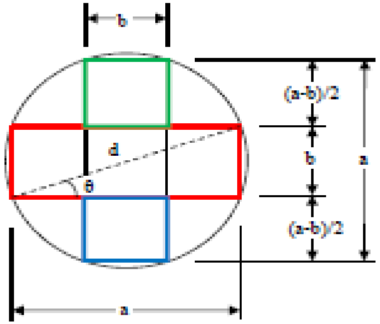
- From the figure,

$$\cos\theta = \frac{a}{d} \Rightarrow \therefore a = d\cos\theta$$

$$\sin\theta = \frac{b}{d} \Rightarrow \therefore b = d\sin\theta$$

TWO STEPPED CORE (CRUCIFORM)

Two stepped core can be divided in to 3 rectangles. Referring to the fig shown,



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

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

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

On substituting 'a' and 'b' in the above equations,

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

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

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

For max value of 'θ',

$$\frac{dA_{gi}}{d\theta} = 0$$

TWO STEPPED CORE (CRUCIFORM)

i.e., $$\frac{dA_{gi}}{d\theta} = d^2 2\cos 2\theta - d^2(2\sin\theta\cos\theta) = 0$$

$$d^2 2\cos 2\theta = d^2(2\sin\theta\cos\theta)$$

$$2\cos 2\theta = \sin 2\theta$$

$$\frac{\sin 2\theta}{\cos 2\theta} = 2$$

$$\tan 2\theta = 2$$

$$2\theta = \tan^{-1}(2)$$

$$\theta = \frac{1}{2}\tan^{-1}(2) = 31.72^0$$

Therefore, if the $\theta=31.72^0$, the dimensions 'a' & 'b' will give maximum area of core for a specified 'd'.

$$\cos\theta = \frac{a}{d} \Rightarrow \therefore a = d\cos\theta \Rightarrow a = d\cos(31.72^0) = 0.85d$$

$$\sin\theta = \frac{b}{d} \Rightarrow \therefore b = d\sin\theta \Rightarrow b = d\sin(31.72^0) = 0.53d$$

Gross core area,

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

$$A_{gi} = 2(0.85d)(0.53d) - (0.53d)^2$$

$$A_{gi} = 0.618d^2$$

$$\textit{Let stacking factor}, S_f = 0.9,$$

$$\textit{Net core area}, A_i = \textit{Stacking factor X Gross Core area}$$

$$A_i = 0.9 \times 0.618d^2 = 0.56d^2$$

The ratios,

$$\frac{\textit{Net core area}}{\textit{Area of Circumscribing circle}} = \frac{0.56d^2}{\frac{\pi}{4}d^2} = 0.71$$

$$\frac{\textit{Gross core area}}{\textit{Area of Circumscribing circle}} = \frac{0.618d^2}{\frac{\pi}{4}d^2} = 0.79$$

Core area factor,

$$K_C = \frac{\textit{Net Core area}}{\textit{Square of Circumscribing Circle}}$$

$$= \frac{A_i}{d^2} = \frac{0.56d^2}{d^2} = 0.56$$

Ratios of Multi-stepped Cores,

Ratio	Square Core	Cruciform Core	3-Stepped Core	4-Stepped Core
$\frac{\textit{Net core area}}{\textit{Area of Circumscribing circle}}$	0.64	0.79	0.84	0.87
$\frac{\textit{Gross core area}}{\textit{Area of Circumscribing circle}}$	0.58	0.71	0.75	0.78
Core area factor, K_C	0.45	0.56	0.6	0.62

CHOICE OF FLUX DENSITY IN CORE

- When hot rolled silicon steel is used for laminations the value for B_m is:

$B_m = 1.1$ to $1.4\ Wb/m^2$ - For distribution transformers

$B_m = 1.2$ to $1.5\ Wb/m^2$ - For power transformers

- When cold rolled silicon steel is used for laminations the value for B_m is:

$B_m = 1.55\ Wb/m^2$ - For transformers with voltage rating upto 132 kV

$B_m = 1.6\ Wb/m^2$ - For transformers with voltage rating 132 kV to 275 kV

$B_m = 1.7\ Wb/m^2$ - For transformers with voltage rating 275 kV to 400 kV

WINDOW SPACE FACTOR

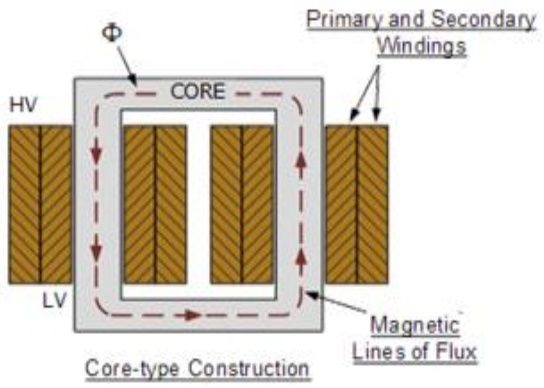
- Window space factor ,$K_w = \frac{Copper\ area\ in\ window}{Total\ window\ area}$

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

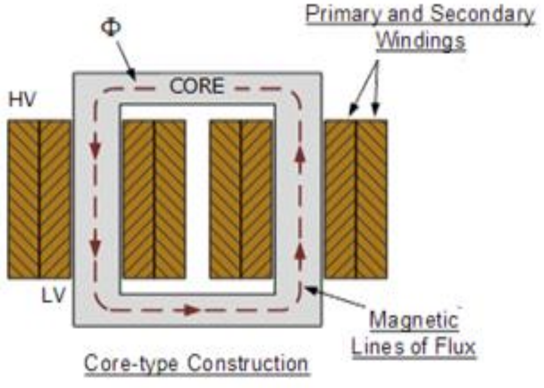
- K_w depends upon the relative amount of insulation and copper provided which in turn depends upon the voltage rating and output of transformer
- $K_w = \frac{8}{(30+kV)}$ [Ratings about 20kVA]
- $K_w = \frac{10}{(30+kV)}$ [Ratings between 50 to 200 kVA]
- $K_w = \frac{12}{(30+kV)}$ [Ratings above 250kVA i.e. about 1000kVA]
- kV is voltage of hv winding

WINDOW DIMENSIONS

- The leakage reactance is affected by the distance between the adjacent limbs
- If this distance is relatively small, the width of the winding is limited and this must be counter balanced by increasing height of the winding.
- Thus the windings are long and thin
- This results in low value of leakage reactance



- If the height of the window is limited ,the width of the window has to be increased in order to accommodate the coils.
- This results in short and wide coils
- This gives large value of leakage reactance
- The height and width of the window can be adjusted to give a suitable arrangement of windings and also to give a desired value of leakage reactance



- $K_w = \frac{A_c}{A_w}$
- $A_w = \frac{A_c}{K_w}$
- $\boldsymbol{A_w = \frac{2a_pT_p}{K_w}}$ for single phase transformer
- $\boldsymbol{A_w = \frac{4a_pT_p}{K_w}}$ for three phase transformer
- A_w= height of window x width of window = H_wx W_w
- $\frac{H_W}{W_w}$ is between 2 to 4

WIDTH OF WINDOW FOR MAXIMUM OUTPUT

- D- Width of iron + width of bare conductors + width of insulation and clearance
- d-width occupied by iron
- Width of window which gives maximum output is, $\boldsymbol{W_W}$**=D - d = 0.7d**

DESIGN OF YOKE

- For rectangular section yokes,
- Area of yoke A_Y = depth of yoke * height of yoke

  $= D_Y * H_Y$
- D_Y = weight of largest core stamping

  = a
- A_Y = (1.15 to 1.25) A_{gi} for transformers using hot rolled steel

  = A_{gi} for transformers using grain oriented steel

DESIGN OF WINDINGS

- The transformer has one high voltage winding and one low voltage winding.
- The **design of winding** involves the **dimensions of number turns and area of cross section of the conductor** used for winding
- The **number of turns** is **estimated** using **voltage rating and emf per turn**(or by using ampere turns and rated current)
- The **area** of cross section is **estimated** using **rated current and current density**
- Usually number of turns in low voltage winding is estimated first and then number of turns in high voltage winding are chosen to satisfy the voltage rating of transformer
- $T_{LV} = V_{LV} / E_T$ or AT / I_{LV}
- $T_{HV} = T_{LV} * (V_{HV} / T_{LV})$
- Same Current density is assumed for both primary and secondary
- Current in primary winding $I_p = \frac{kVA*103}{V_p}$

Contd…

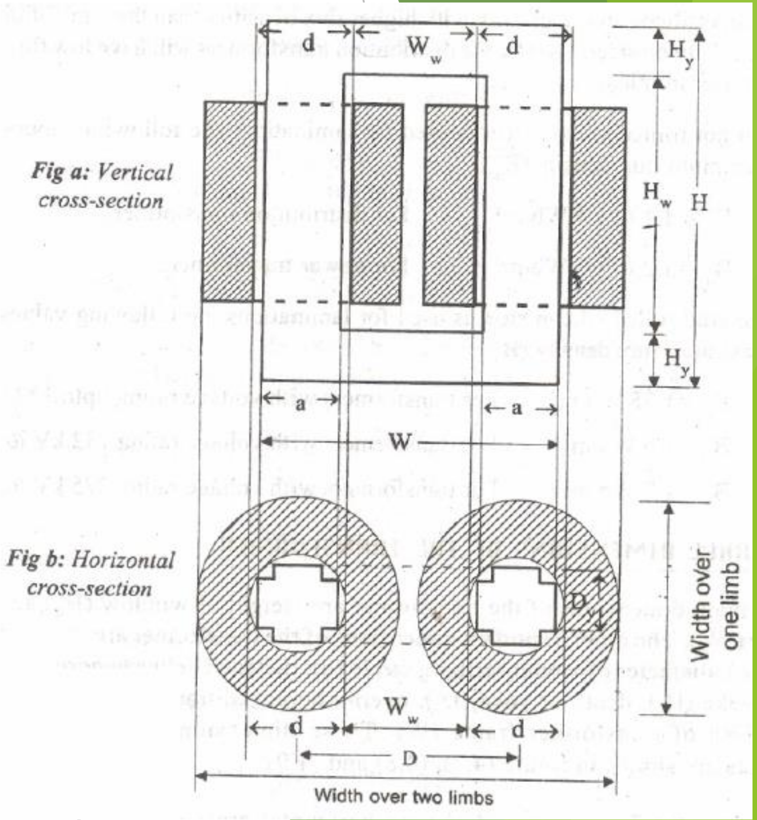
- Area of cross section of Primary Winding, $\mathbf{a_p = I_p / \delta}$
- Area of cross section of Secondary Winding, $\mathbf{a_s = I_s / \delta}$
- **δ = 1.1 to 2.2 A/mm^2 for distribution transformer**
- **δ = 2.2 to 3.2 A/mm^2 for large power transformer** with self oil cooling or air blast
- **δ = 5.4 to 6.2 A/mm^2 for large power transformer** with forced circulation of oil or with water cooling coils

OVERALL DIMENSIONS

- Main Dimensions of transformer are
  - **W_W – Width of window**
  - **H_W – Height of the window / Length of limb**
- The other dimensions are
  - **a - width of largest stamping**
  - **d – diameter of circumscribing circle**
  - **D – distance between centers of adjacent limbs**
  - **D_Y – Depth of the yoke**
  - **H_Y – Height of the yoke**
  - **H – Overall height of transformer over yokes / Overall height of frame**
  - **W – Length of yoke / Overall width of frame**

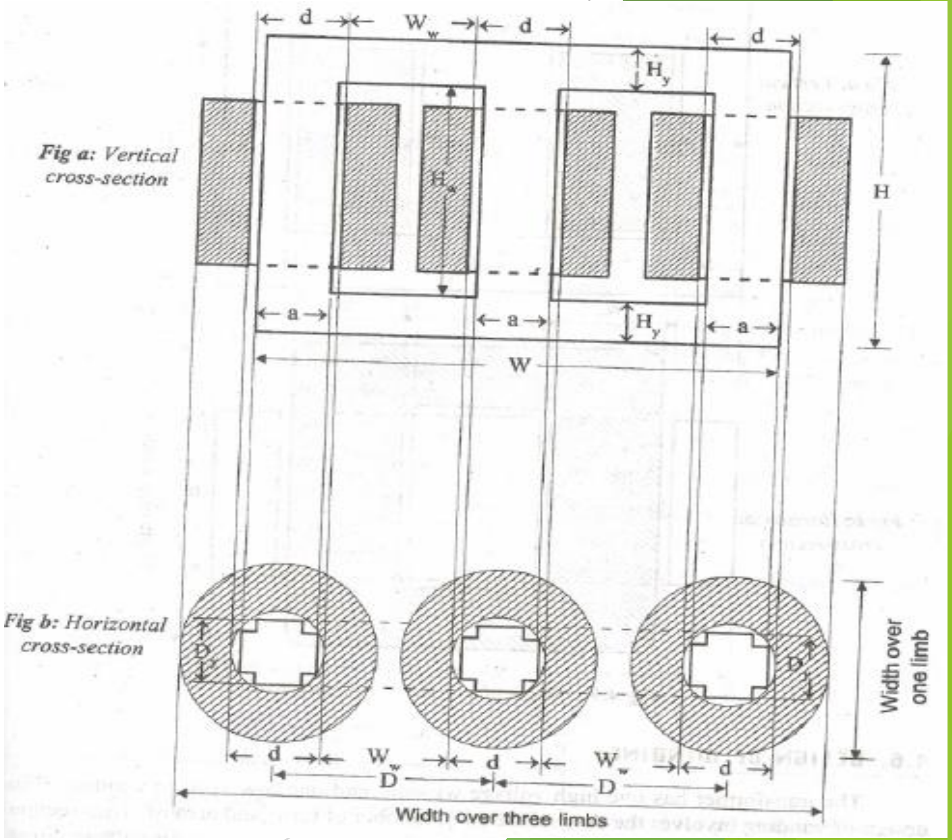
Single Phase Core Type Transformer

- $D = d + W_W$
- $D_Y = a$
- $H = H_W + 2H_Y$
- $W = D + a$
- Width over two limbs = D + Outer diameter of H.V. winding
- Width over one limbs = Outer diameter of H.V. winding



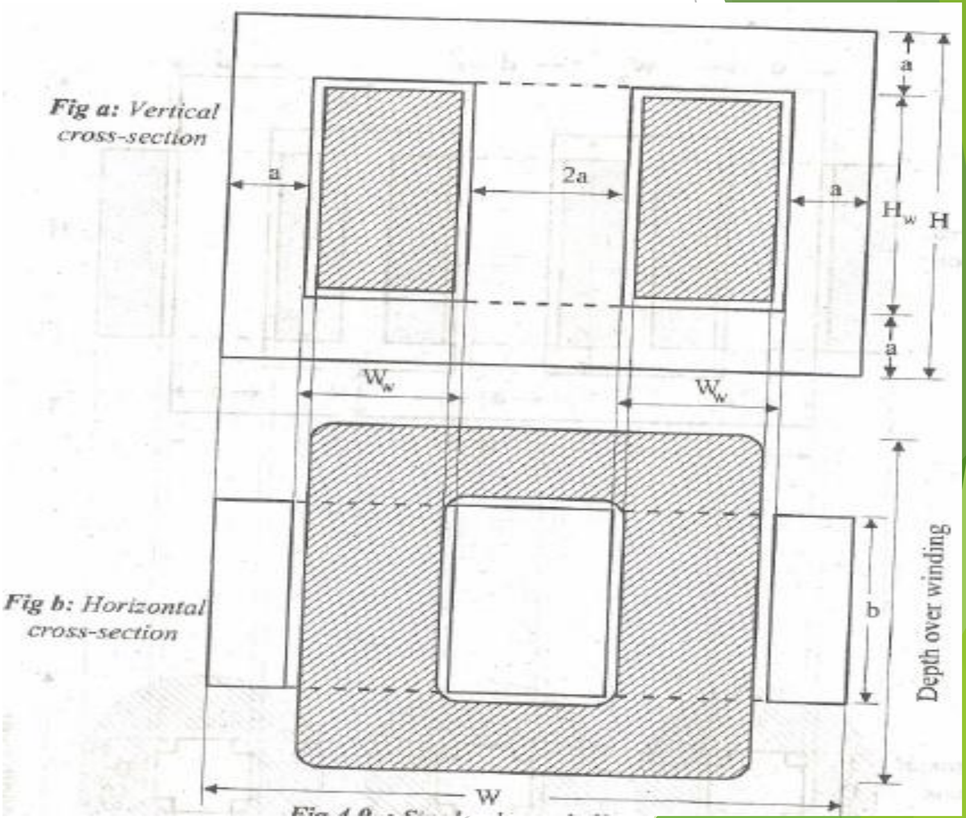
Three Phase Shell Type Transformer

- $D = d + W_W$
- $D_Y = a$
- $H = H_W + 2H_Y$
- $W = 2D + a$
- Width over three limbs = 2D + Outer diameter of H.V. winding
- Width over one limbs = Outer diameter of H.V. winding



Single Phase Shell Type Transformer

- $D_Y = b$
- $H_Y = a$
- $W = W_W + 4a$
- $H = H_W + 2H_Y$



Design of tanks with cooling tubes

Let, Dissipating surface of tank – S_t

Dissipating surface of tubes – XS_t

Loss dissipated by surface of the tank by radiation and convection = $(6+6.5)S_t = 12.5S_t$

$$\left.\begin{array}{l}\textit{Loss dissipated by}\\ \textit{tubes by convection}\end{array}\right\} = 6.5 \times \frac{135}{100} \times XS_t = 8.8XS_t$$

$$\left.\begin{array}{l}\textit{Total loss dissipated}\\ \textit{by walls and tubes}\end{array}\right\} = 12.5S_t + 8.8XS_t = (12.5 + 8.8X)S_t \rightarrow (1)$$

$$\text{Actual total area of tank walls and tubes} = S_t + XS_t = S_t(1+X)$$

$$\text{Loss dissipated per m}^2\text{ of dissipating surface} = \frac{\text{Total losses dissipated}}{\text{Total area}}$$

$$\text{Loss dissipated per m}^2\text{ of dissipating surface} = \frac{S_t(12.5+8.8X)}{(1+X)} = \frac{(12.5+8.8X)}{(1+X)} \rightarrow (2)$$

$$\left.\begin{array}{l}\text{Temperature rise in}\\ \text{Transformer with cooling tubes}\end{array}\right\}\theta = \frac{\text{Total loss}}{\text{Loss Dissipated}}$$

$$\text{Total losses, } P_{loss} = P_i + P_c \quad \rightarrow (3)$$

$$\text{From (1) and (3), we have, } \theta = \frac{P_i + P_c}{S_t(12.5+8.8X)}$$

$$(12.5+8.8X) = \frac{P_i + P_c}{\theta\ S_t}$$

$$8.8X = \frac{P_i + P_c}{\theta\ S_t} - 12.5 \quad \Rightarrow \qquad X = \frac{1}{8.8}\left(\frac{P_i + P_c}{\theta\ S_t} - 12.5\right)$$

$$\text{Total area of cooling tubes} = \frac{1}{8.8}\left(\frac{\mathrm{P_i} + \mathrm{P_c}}{\theta\, S_t} - 12.5\right)S_t = \frac{1}{8.8}\left(\frac{\mathrm{P_i} + \mathrm{P_c}}{\theta} - 12.5 S_t\right) \rightarrow (5)$$

Let, l_t – *Length of tubes*

d_t – *Diameter of tubes*

$\therefore$ *Surface area of tubes* $= \pi\, d_t l_t$

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

$$n_t = \frac{1}{8.8\pi\, d_t l_t}\left(\frac{\mathrm{P_i} + \mathrm{P_c}}{\theta} - 12.5 S_t\right) \rightarrow (6)$$

- For single phase transformer

  Width of the tank $W_t = D + D_e + 2b$

- For three phase transformer

  Width of the tank $W_t = 2D + D_e + 2b$

- Length of the tank $L_t = D_e + 2l$
- Height of the tank $H_t = H + h_1 + h_2$
- where,

  D = distance between adjacent limbs

  D_e = external diameter of H.V. winding

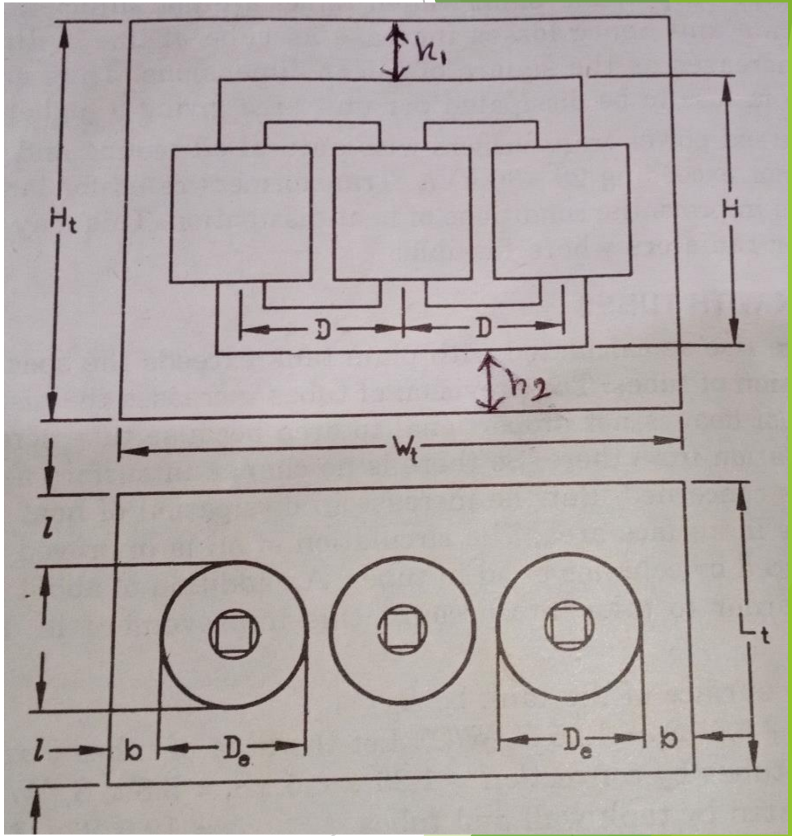
  b = clearance between H.V. winding and tank along width

  l = clearance on each side between the winding and tank along the length

  H = height of the transformer frame

  h_1 = Clearance b/w the transformer frame and tank at the top

  h_2 = Clearance b/w the transformer frame and tank at the bottom



Tank Dimensions

Typical values of clearances

Voltage kV	Rating kVA	Clearance mm		
		b	l	h
11 kV or less	less than 1000	40	50	450
	1000—5000	70	90	420
about 11 kV and upto 33 kV	less than 1000	75	100	550
	1000—5000	85	125	550

COOLING OF TRANSFORMER

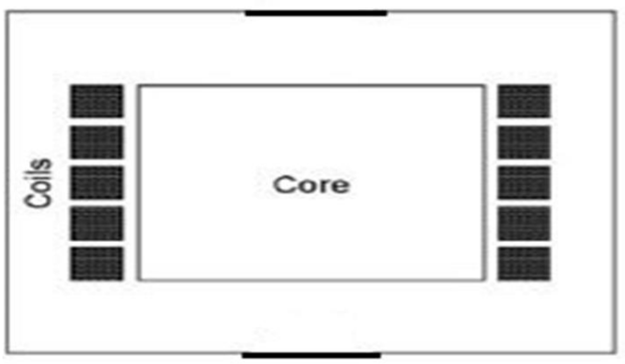
- **Cooling of Transformer** is the process by which heat generated in the transformer is dissipated or treated to the safe value. This is achieved by various cooling methods of transformer available
- The major factor for the generation of heat in the transformer is the various losses like hysteresis, eddy current, iron, and copper loss. Among all the various losses the major contributor of the heat generation is the **copper loss** or I^2R loss
- If the temperature of the transformer continue to increase rapidly, it will result in the **degradation of the insulation** used in the transformer resulting in the damaging of the various parts and hence the failure of the transformer.
- Thus, proper removal or treatment of heat is necessary for the efficient working, longer life and higher efficiency of the transformer.
- The various coolants used for the cooling purpose of the transformer are air, synthetic oils, mineral oils, gas, water.

COOLING METHODS OF TRANSFORMER

- **For dry type transformers**
  - Air Natural (AN)
  - Air Blast
- **For oil immersed tranformers**
  - Oil Natural Air Natural (ONAN)
  - Oil Natural Air Forced (ONAF)
  - Oil Natural Water Forced (ONWF)
  - Oil Forced Air Forced (OFAF)
  - Oil Forced Water Forced (OFWF)

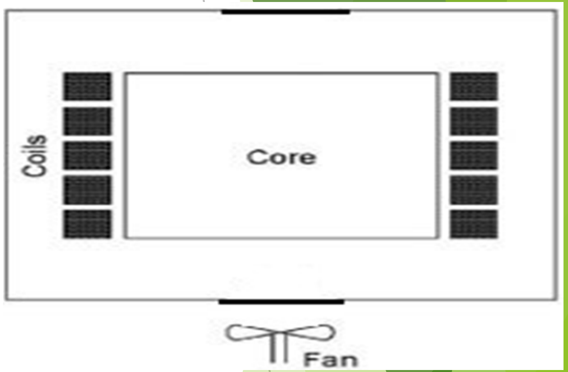
AIR NATURAL (AN)

- By Air Natural method the generated heat in the transformer is cooled by the circulation of **natural air**.
- When the temperature of the transformer becomes higher as compared to the temperature of the surrounding air, thus by the process of natural **convection**, heated air is replaced by the cool air.
- This method is also known as a **self-cooled method**.
- This method is used for cooling the **smaller output transformer** rating that is up to **1.5 MVA**.



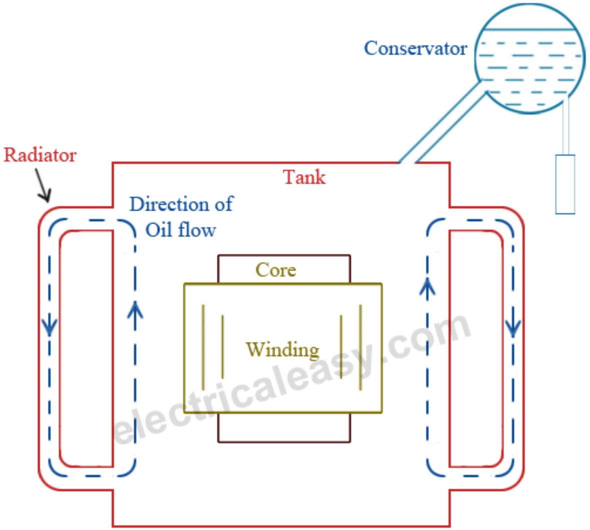
Air Forced (AF) or Air Blast

- For transformers rated more than 3 MVA, cooling by natural air method is inadequate.
- In this method, the heat generated is cooled by the **forced air circulation** method.
- With the help of fans and blowers, air is forced on the core and the windings of the transformer.
- As the temperature inside the transformer goes beyond the standard safe level, an alarm is activated, and the fans and blowers are switched ON automatically.
- The air supply must be filtered to prevent the accumulation of dust particles in ventilation ducts.
- This method is used for transformer rating up to **15MVA.**



Oil Natural Air Natural (ONAN)

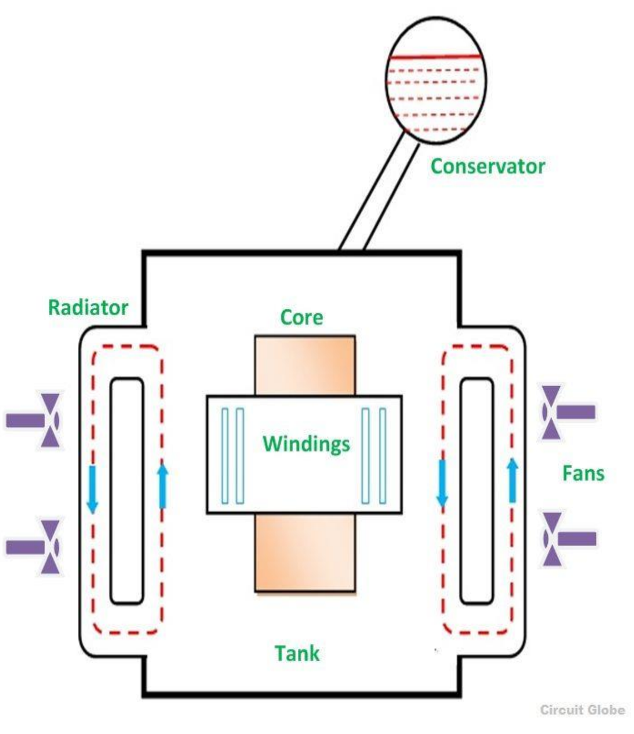
- This method is used for **oil immersed transformers**.
- In this method, the heat generated in the core and winding is transferred to the oil.
- The **heated oil flows in the upward** direction and then in the radiator.
- The vacant place is filled up by cooled oil from the radiator.
- The heat from the oil will dissipate in the atmosphere due to the natural air flow around the transformer.
- In this way, the oil in transformer keeps circulating due to natural convection and dissipating heat in atmosphere due to natural conduction.
- This method can be used for transformers **upto about 30 MVA**.



Oil Natural Air Natural (ONAN) - Cooling of Transformer

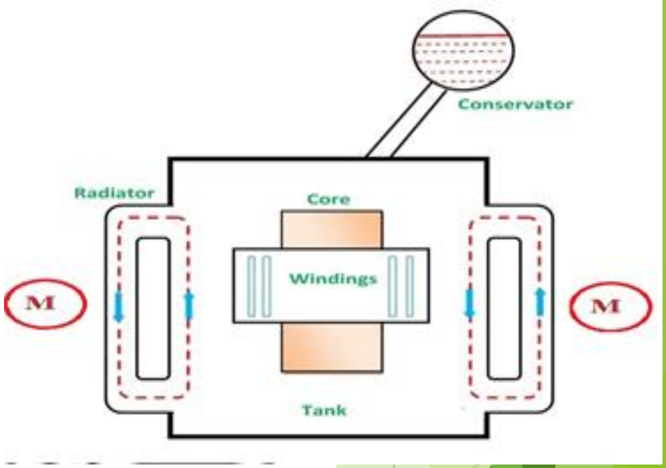
Oil Natural Air Forced (ONAF)

- ONAF method is used for the cooling of the transformer of rating up to **60 MVA.**
- As discussed above that in ONAN method, the dissipation of heat is taking place by the convection process in which air is naturally circulated to cool down, but in this type, the **forced air** is used for the purpose of cooling the transformer.
- Forced air provides **faster heat dissipation** than natural air flow.
- In this method, fans are mounted near the radiator, a high velocity of air is forcefully applied to the radiator which will help in cooling oil more quickly and efficiently.
- Its cost is higher as compared to another process where the circulation of oil and air is done naturally because a fan and blowers are attached as extra cooling equipment, in this method.



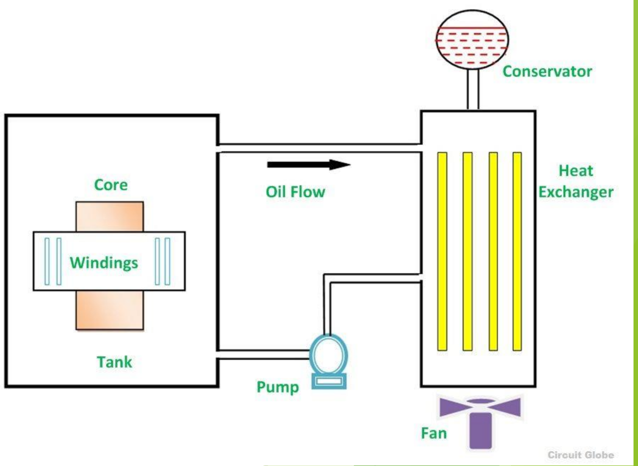
Oil Natural Water Forced (ONWF)

- In Oil Natural Water Force cooling method, the transformer core and the windings are immersed in the oil tank.
- A radiator is installed outside the tank, as the temperature rises and the oil heats up and moves upward, the heat is dissipated by the natural process of convection and oil is passed through the radiator, but the water is pumped and passed through the heat exchanger for cooling of the oil.



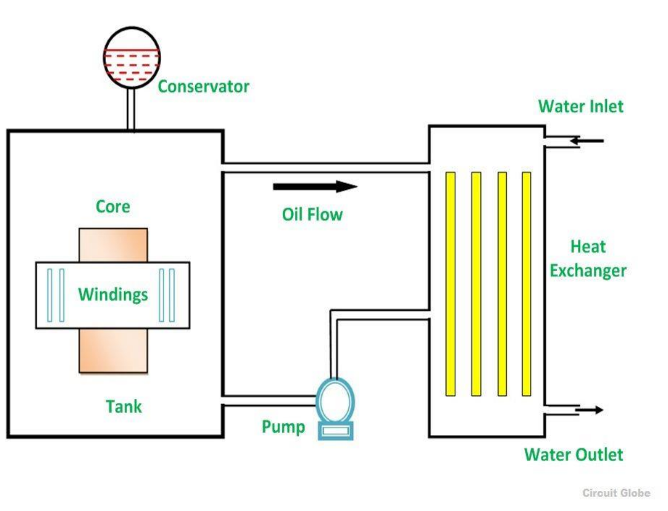
Oil Forced Air Forced (OFAF)

- As the name itself says that both the oil and the air are applied by force for cooling of a transformer.
- The Heat Exchanger is installed through which hot oil is circulated with the help of a pump. Air is forced to pass on the heat exchanger with the help of high-speed fans.
- This method is similar to ONAN, as when there is low load on the transformer the cooling is done by a simple ONAN method. However, as soon as the load is increased, the generated heat will also be more and therefore the sensor gives an alarm that the dissipation of heat has exceeded the safe value and as a result, the fans and pumps are switched on automatically. Thus, the cooling takes place by OFAF method
- This type of cooling is provided for higher rating transformers at substations or power stations



Oil Forced Water Forced (OFWF)

- A heat exchanger is installed through which both oil and water are passed with the help of a pump.
- Forced water flow is used to dissipate heat from the heat exchangers
- The oil is forced to flow through the heat exchanger with the help of a pump, where the heat is dissipated in the water which is also forced to flow.
- The heated water is taken away to cool in separate coolers.
- The level and pressure of the oil are always kept higher than that of water
- This type of method is suitable for **large capacity** of the transformer having rating as **several hundred MVA** or where banks of transformers are installed.
- Mainly this type of cooling is done for the transformer installed at the **hydropower plant.**



ELECTRICAL MACHINE DESIGN

MODULE 3

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SELECTION OF NUMBER OF POLES

- Appropriate value of magnetic loading and electric loading is required in order to get right design of a machine. So far magnetic loading is concerned, suitable number of pole is must.
- In case of AC machine supply frequency and speed of machine fixes the number of pole.
- While in case of DC machine any number of pole can be selected. However a small range of number of pole gives good commercial design.

Selection of number of poles

It depends on:

1. Frequency
2. Weight of iron part
3. Weight of copper
4. Length of commutator
5. Flash over
6. Distortion of field form
7. Labour charges

1) Frequency

$$f = \frac{pn}{2}$$

- Frequency of flux reversal increases with the increase in number of pole. In DC machine large frequency of reversal leads to excessive iron loss in armature core and teeth.
- To maintain above said losses, frequency of reversal is kept 25-50 Hz for common ratings.
- But will be more in some small machines typically high speed DC series motors

2) Weight of iron part

- YOKE AREA
- ARMATURE CORE AREA

YOKE AREA

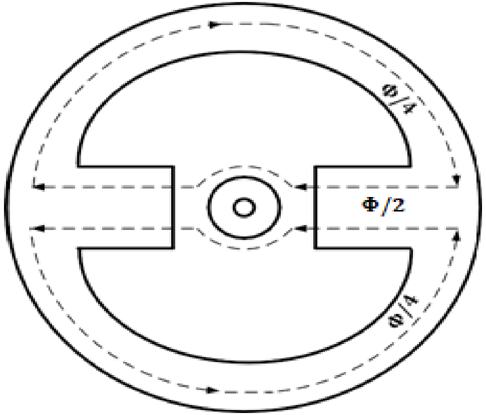


Figure 3. 3 Two pole machine

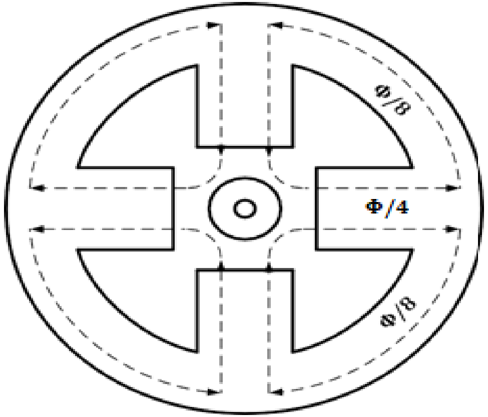


Figure 3. 4 Four pole machine

$\phi =$ Total flux around the airgap

$\frac{\phi}{2} =$ Flux per pole

$\frac{\phi}{4} =$ Flux in yoke

$\frac{\phi}{4} =$ Flux in armature core

$\phi =$ Total flux around the airgap

$\frac{\phi}{4} =$ Flux per pole

$\frac{\phi}{8} =$ Flux in yoke

$\frac{\phi}{8} =$ Flux in armature core

- Flux carried by yoke is inversely proportional to number of pole, so for more number of pole, yoke cross section area required is less. As yoke carries almost steady flux, iron loss is negligible and hence large number of pole can be good choice to reduce weight of yoke.

ARMATURE CORE AREA

- Flux per pole divides itself in two parts in armature core, so for more number of pole, armature core cross section area required is less. But increased number of pole increases the iron loss in armature core due to increased frequency of reversal.

- Eddy current loss in armature core

2 POLE MACHINE	4 POLE MACHINE
$P_e \alpha\ B_c^2 f^2$	$P_e \alpha\ B_c^2 f^2$
$P_e \alpha \left(\frac{\phi_c}{A_c}\right)^2 \left(\frac{pn}{2}\right)^2$	$P_e \alpha \left(\frac{\phi_c}{A_c}\right)^2 \left(\frac{pn}{2}\right)^2$
$P_e \alpha \left(\frac{\phi}{4A_c}\right)^2 \left(\frac{2n}{2}\right)^2$	$P_e \alpha \left(\frac{\phi}{8A_c}\right)^2 \left(\frac{4n}{2}\right)^2$
$P_e \alpha \frac{\phi^2 n^2}{16A_c^2}$	$P_e \alpha \frac{\phi^2 n^2}{16A_c^2}$

- To obtain same eddy current loss for all value of number of pole, area of armature core has to be same. Armature core area decreases for large number of pole, eddy current loss increases.

- Hysteresis loss in armature core

2 POLE MACHINE

$$P_h \alpha\ B_c^2 f$$

$$P_h \alpha \left(\frac{\phi_c}{A_c}\right)^2 \left(\frac{pn}{2}\right)$$

$$P_h \alpha \left(\frac{\phi}{4A_c}\right)^2 \left(\frac{2n}{2}\right)$$

$$P_h \alpha \frac{\phi^2 n}{16A_c^2}$$

4 POLE MACHINE

$$P_h \alpha\ B_c^2 f$$

$$P_h \alpha \left(\frac{\phi_c}{A_c}\right)^2 \left(\frac{pn}{2}\right)$$

$$P_h \alpha \left(\frac{\phi}{8A_c}\right)^2 \left(\frac{4n}{2}\right)$$

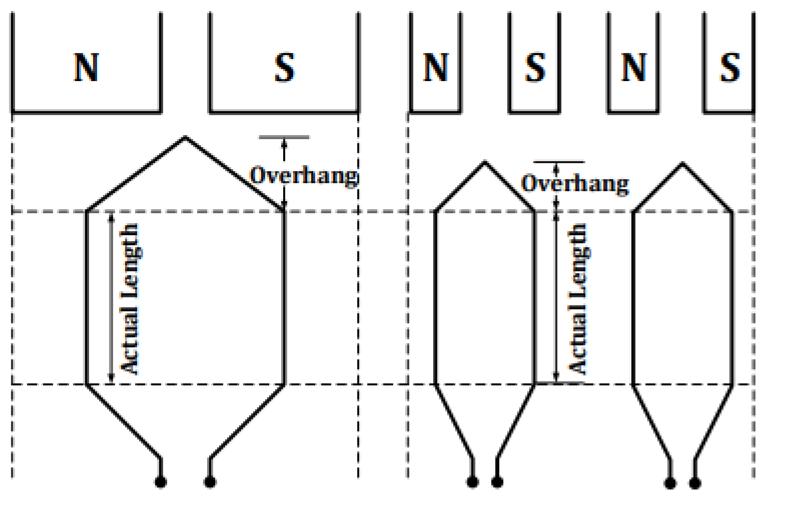
$$P_h \alpha \frac{\phi^2 n}{32A_c^2}$$

- Hysteresis loss decreases with increase in number of pole.
- By decreasing the number of poles the weight of the iron in the armature core can be decreased.

3)Weight of copper

ARMATURE COIL

- Portion of conductor accommodated in slot contributes in production of emf and torque. Therefore it is called active copper.
- While portion of conductor in overhang only provides connection between active parts, it does not contribute in production of emf and torque. Therefore it is called inactive copper.



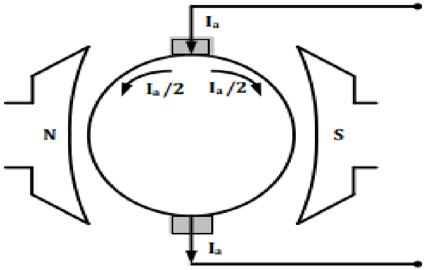
- As the ratio of inactive copper to active copper is less, machine becomes cheaper.
- Weight of inactive copper varies inversely with number of poles.
- For constant diameter, pole pitch decreases with the increase in number of pole which further reduces the length of conductor in overhang portion. So, it is clear that copper used in two pole machine is more than copper used in four pole machine. Also overhang projected outside the core is more in case of two pole machine which gives large overall length of machine.
- INCREASE IN NUMBER OF POLES REDUCES WEIGHT OF COPPER IN ARMATURE

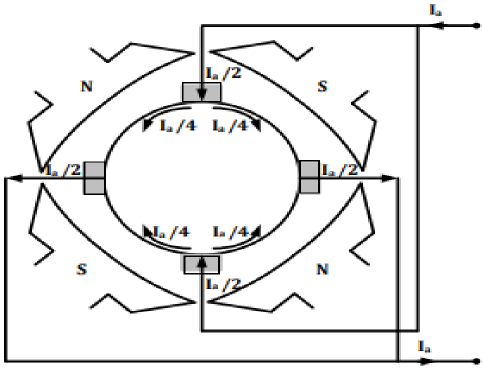
FIELD COIL

- As field mmf is inversely proportional to number of pole, two pole machine will have more field mmf required compared to four pole machine. This means weight of copper, number of turns, mean turn length and field copper loss is more in case of two pole machine.
- Total weight of copper of both armature and field windings decreases with increase in number of poles

4) Length of commutator

- Current collected by each brush arm depends on number of pole.
- More number of pole means current per brush arm is less and hence less area and thickness of brush. Reduction in brush thickness results in reduction in length of commutator and overall length of machine.





5) Flash over

- Number of brush arms is equal to the number of poles. For same diameter of commutator, the distance between adjacent brush arms decreases as the number of pole is increased, hence it leads to the possibility of flash over between the adjacent brush arms.
- Alternatively , to avoid possibility of flash over diameter of the commutator will have to be increased as the number of poles increases.

6)Distortion of field form

- Armature mmf per pole: $AT_a = \frac{ac}{2}$X polepitch = $\frac{ac}{2}$X $\frac{\pi D}{p} = \frac{AC}{2p}$
- The armature mmf per pole varies inversely with number of poles.
- Hence with a smaller number of poles, the armature mmf per pole increases resulting in distortion of field form and reduction in flux under load conditions.
- Distortion in flux causes poor commutation conditions and sparking
- Causes reduced generated emf
- To reduce the effect compensating windings are used
- This complicates the construction and increases the cost of the machine

7) Labour charge

- EMF generated, E=$\frac{\Phi Znp}{a}$
- pΦ is assumed to be constant
- E α Zn/a
- For lap winding a=p, E α Zn/p
- Z α Ep/n
- So number of conductor and armature coil increases with the increase in number of pole.
- For wave winding a=2, so number of conductor and armature coil is independent of number of pole.
- Number of commutator segments are same as number of armature coil, means more number of commutator segments for more number of pole.
- Also, number of field coil is same as number of pole, means more number of field coils needs to be assembled for more number of pole.
- Hence, labour charge for armature coil and field coil winding increases with increase in number of pole.

Guidelines for selection of number of pole

- Frequency of flux reversal in armature core should be between 25 to 50 Hz.
- Current per parallel path should not be more than 200 A.
- Current per brush arm should not be more than 400 A.
- Armature mmf should not be too large.

1) Core length

Factors affecting the length of core:

- i) Cost : the manufacturing cost of a machine with large core length, is less. This is because the proportion of inactive copper to active copper is smaller for greater the length of core. Therefore it is desirable to have large core length for less cost.
- ii) Ventilation: the ventilation of large core length is difficult because the central portion of the core tends to attain a high temperature rise. If long armature are necessary special means for ventilation of core must be provided.

Limiting value of core length

- The emf induced in a conductor(e_z) should not exceed $\frac{7.5}{T_C N_C}$ in order that the maximum voltage between adjacent segments at load is limited to 30 V.
- The voltage in a conductor at no load $e_Z = B_{av} \text{L} V_a$
- For a limiting case: $B_{av} \text{L} V_a = \frac{7.5}{T_C N_C}$
- Limiting value of core length L = $\frac{7.5}{B_{av} V_a T_C N_C}$
- B_{av} = average gap density Wb/m2
- V_a = peripheral speed, m/s
- T_C = turns per coil
- N_C = number of coils between adjacent segments

2) Armature diameter

- The peripheral speed lies between 15 to 50 m/s.
- Normally the peripheral speed should not exceed 30m/s.
- If speed exceeds 30m/s then special methods have to be employed to prevent the overhang from flying out due to excessive centrifugal force

- The diameter should be suitable for accommodating desired number of poles with normal values of pole pitch

POLE	POLE PITCH(mm)
2	Upto 240
4	240 to 400
6	350 to 450
Above 6	450 to 500

LIMITING VALUE OF ARMATURE DIAMETER

$P_a \simeq EI_a \times 10^{-3}$ kW.

E = emf per conductor × conductors per parallel path

$= e_z\, Z/a.$

$$P_a = \left(e_z \frac{Z}{a}\right) I_a \times 10^{-3} = e_z \frac{I_a}{a} Z \times 10^{-3} = e_z \pi D\, ac \times 10^{-3}$$

$$D = \frac{P \times 10^3}{\pi\, ac\, e_z}$$

Specific electric loading, $\mathbf{ac} = \frac{I_z Z}{\pi D} = \frac{I_a}{a} \cdot \frac{Z}{\pi D}$

$$\therefore \frac{I_a Z}{a} = \pi D\, \mathbf{ac}$$

∴ Maximum value of armature diameter, $D_{max} = \dfrac{P_a \times 10^3}{\pi\, \mathbf{ac}\, e_z}$

LENGTH OF AIR GAP FOR DC MACHINES

The value of air gap depends on several factors.

Armature reaction

- To overcome effect of distorted field form due to armature reaction, field mmf is made larger than armature mmf.
- Large air gap draws large field mmf, hence machine with large air gap has less distorting effect of armature reaction. But large field mmf results in increased cost and size of machine.

Circulating current

- Small irregularity in air gap results in large circulation current in lap wound machine. So, large air gap is preferred for lap wound machine.

Pole face loss

- Pole face losses reduces if large value of air gap is selected.

Noise

- Operation of machine with large air gap is silent.

Cooling

- Cooling of machine with large air gap is better.

Mechanical aspects

- Small air gap value leads to unbalanced magnetic pull and causes rotor to foul with stator. So the length of air gap should be large to prevent any such possibility

Estimation of air gap length

AT_a = Armature mmf per pole (AT)

AT_g = Air gap mmf (AT)

B_g = Maximum flux density in the air gap (Wb/m^2)

l_g = Air gap length (mm)

k_g = Gap contraction factor

$$AT_g = (0.5 \text{ to } 0.7) AT_a = (0.5 \text{ to } 0.7)\left(\frac{ac \times \tau}{2}\right)$$

Also,

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

So,

$$8{,}00{,}000 B_g l_g k_g = (0.5 \text{ to } 0.7)\left(\frac{ac \times \tau}{2}\right)$$

$$l_g = \frac{(0.5 \text{ to } 0.7)\left(\frac{ac \times \tau}{2}\right)}{8{,}00{,}000 B_g k_g}$$

$$\text{Armature mmf per pole} = \frac{I_z(Z/2)}{p} = \frac{I_z Z}{2p} = \frac{\mathbf{ac}\pi D}{2p} = \frac{\mathbf{ac}\ \tau}{2}$$

$$\left(\because\ \mathbf{ac} = \frac{I_z Z}{\pi D} \quad \text{and} \quad \tau = \frac{\pi D}{p}\right)$$

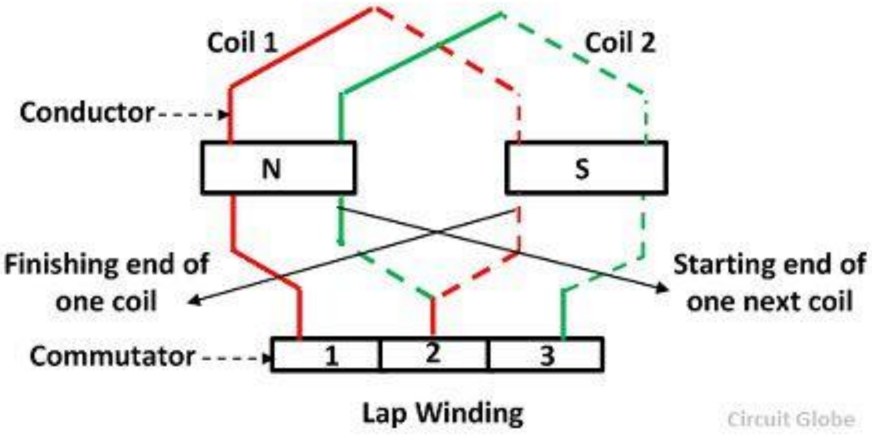
- K_g may be assumed as 1.15
- Usually value of air gap length lies between 0.01 to 0.015 of pole pitch

ARMATURE WINDING

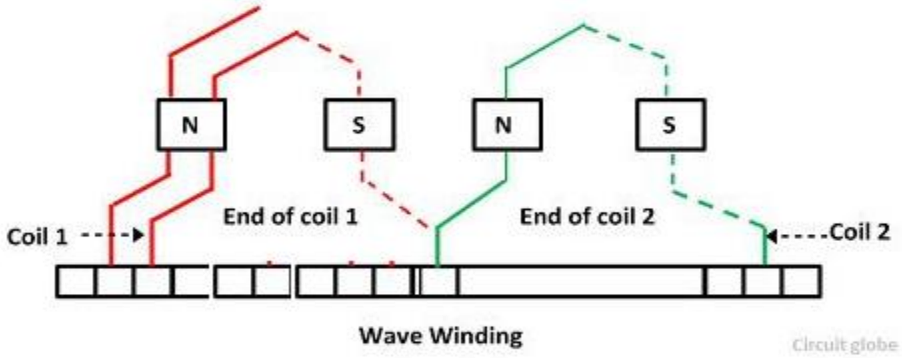
- In general armature winding consists of number of coils connected in series and number of such series circuits are connected in parallel
- Coils may be single turn or multi turn
- A turn consists of 2 conductors
- Coils are placed in slots on the armature periphery
- For full pitched winding the two coil sides of a coil are placed one pole pitch apart.
- Double layer winding means each slot has two coil side

TYPES OF ARMATURE WINDING

- Simplex lap winding
  - Number of parallel path is equal to number of poles **(a = p)**
  - The end of the armature coil is connected to an adjacent segment on the commutators.



- Simplex wave winding
  - Number of parallel path is equal to two **(a=2)**
  - The end of the armature coil is connected to commutator segments some distance apart.



DIFFERENCE

In lap winding, $a = p$

$$I_z = \frac{I_a}{a} = \frac{I_a}{p}$$

$$Z = \left(\frac{60E}{\phi pN}\right)a = \left(\frac{60E}{\phi pN}\right)(p)$$

Lap winding	Wave winding
1. The number of parallel paths is equal to number of poles.	1. The number of parallel paths is two.
2. Current through a conductor is I_a/p, where I_a is armature current and p is number of poles.	2. Current through a conductor is $I_a/2$ where I_a is armature current.
3. For a specified voltage rating, the number of armature conductors required is p/2 times that of wave winding.	3. For a specified voltage rating, the number of armatuıe conductors required is 2/p times that of lap winding.
4. For a specified current rating the area of cross-section of conductor is 2/p times that of wave winding.	4. For a specified current rating the area of cross-section of conductor is p/2 times that of lap winding.
5. For a specified power rating large number of conductors with smaller area of cross-section is required. But the volume of copper is same as that of wave winding.	5. For a specified power rating less number of conductors with larger area of cross-section is required. But the volume of copper is same as that of lap winding.

In wave winding, $a = 2$

$$I_z = \frac{I_a}{a} = \frac{I_a}{2}$$

$$Z = \left(\frac{60E}{\phi pN}\right)a = \left(\frac{60E}{\phi pN}\right)($$

6. Since the lap winding has large number of conductors, the area required for insulation is more and so slot area will be large. Also the number of coils will be large. Therefore the cost will be high.	6. Since the wave winding has less number of conductors, the area required for insulation is less and so slot area required will be lesser. Also the number of coils will be less. Therefore the cost will be less.
7. Equalizer connections have to be employed.	7. Equalizer connections are not needed.
8. The winding is easier and short pitched coils can be made, which results in reduction in overhang length.	8. It is difficult to wind wave winding and short pitched coils can't be used.
9. The lap winding is used for large capacity machines and when the current rating is more than 400A.	9. The wave winding is used for small and medium capacity machines. Also used for high voltage and slow speed machines.

NUMBER OF ARMATURE CONDUCTORS

- The generated emf in the armature:

  E = V +$I_a r_m$ for generator

  E = V - $I_a r_m$ for motor

  where V = terminal voltage and

  r_m = internal voltage drop

- $\mathbf{E=\frac{\Phi ZN}{60}\frac{p}{a}=\frac{\Phi Znp}{a}}$
- $\mathbf{Z} = \frac{Ea}{\Phi np}$

Factors affecting selection of number of armature slots for DC machines

- **Slot pitch**
- **Cooling of armature conductors**
- **Flux pulsations**
- **Commutation**
- **Cost**

SLOT PITCH

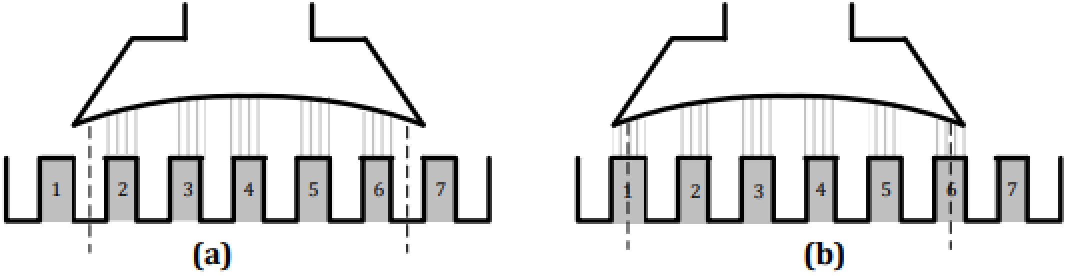
- The slot pitch is a peripheral distance between centers of two adjacent slot in DC machine.
- A large number of slots results in smaller slot pitch and so the width of tooth is also small.
- This may lead to difficulty in construction.

COOLING OF ARMATURE CONDUCTORS

- Large number of slots leads to less number of conductors per slot, so less conductors are bunched together in a slot.
- Hence the cooling of armature conductors is better.

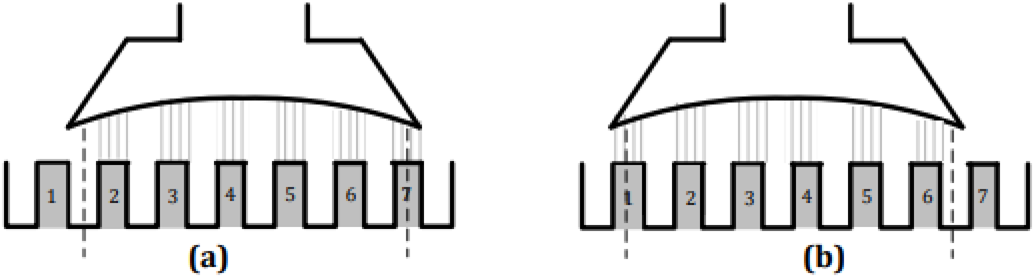
FLUX PULSATIONS

- Change in air gap flux due to slotting is called flux pulsation. This phenomenon gives rise to eddy current loss in pole phase and magnetic noise.
- With larger number of slots flux pulsations are reduced



Flux pulsation with integral number of slots per pole

When flux passes from pole to armature through 5 teeth i.e. (a), if armature moves half slot pitch to the right i.e. (b) flux passes from pole to armature through 6 teeth. Reluctance through air gap at position (a) is greater than at position (b). Hence flux pulsates in air gap as armature rotates.



Flux pulsation with integral+1/2 number of slots per pole

- When flux passes from pole to armature through 5+1/2 teeth i.e. (a), if armature moves half slot pitch to the right i.e. (b) flux passes from pole to armature through 5+1/2 teeth. Reluctance through air gap at position (a) and at position (b) is almost same. Hence no flux pulsations in air gap as armature rotates.
- So, number of slots under pole shoe should be integer+1/2.

COMMUTATION

- For spark less commutation the flux pulsations and oscillations under the inter pole needs to be avoided.
- This can be achieved with large number of slots per pole.
- In fact, the number of slots in the region between the tips of two adjacent poles should be at least 3.

In fact, the number of slots in the region between the tips of two adjacent poles should be at least 3, or

$$(1 - \psi) \times \text{slots per pole} \geq 3$$

Taking $\psi = 0.67$, number of slots per pole, $\frac{S}{p} > \frac{3}{1-0.67} > 9.12.$

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

COST

- Labor cost and slot insulation cost reduces when less number of slots are selected.

Guideline for selection of number of slots

- Slot pitch should lie between 25 to 35 mm.
- Slot loading should not exceed 1500 A.
- Number of slot per pole pair should be odd integer.
- Slot per pole should lie between 9 to 16.
- For wave winding number of slot should not be multiple of pole pair and for lap winding number of slot should be multiple of pole pair.

CROSS SECTION OF ARMATURE CONDUCTORS

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

$$\therefore \text{Armature current, } I_a = \frac{P_a}{E \times 10^{-3}}$$

$$\text{Current through an armature conductor, } I_z = \frac{I_a}{a}$$

where, a = Number of parallel paths.

$$\text{Area of corss - section of armature conductor, } a_a = \frac{I_z}{\delta_a}$$

- δ_a should be taken as high as efficiency and temperature rise conditions permits
- Large value of δ_a reduces size of the conductors and therefore there is savings in the cost of copper
- Also the slot area required becomes small

Let, δ_a = Current density in armature conductor in A/mm^2

For large machine with strap wound armature, $\delta_a = 4.5 A/mm^2$

For small machine with wire wound armature, $\delta_a = 5 A/mm^2$

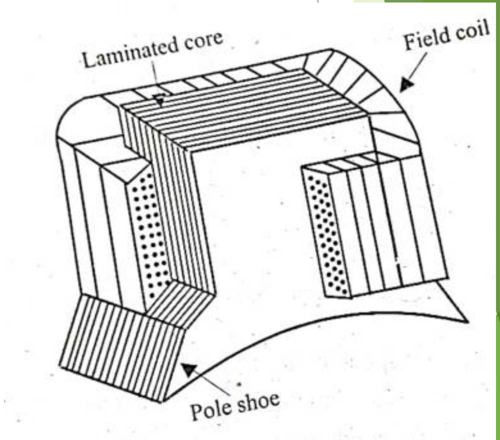
For high speed fan ventilated machine, $\delta_a = 6$ to $7 A/mm^2$

For conductors having small area of cross-section, round wires are used.

For cross-sectional area above 10 mm^2, square or rectangular conductors are used.

FIELD SYSTEM IN DC MACHINE

- The field system consists of:
  - Poles
  - Pole shoe
  - Field winding
- Types of field windings are :
  - shunt field winding
  - series field winding
  - Compound field winding



- Shunt field winding: large number of turns made of thin conductors, because the current carried by them is very low
- Series field winding: carry heavy current and so it is made of smaller number of turns with thick conductors
- Field coils are former wound, insulated and fixed over the field poles.
- In shunt machines, the full winding space along the height of the pole is used to accommodate shunt field winding
- In compound machines, 80% of the winding space is taken by shunt field and the remaining 20% by series field

The factors to be considered for the design of field winding are:

- Mmf per pole and flux density
- Loss dissipated from the surface field coil
- Resistance of field coil
- Current density in field conductors

Design of shunt field winding

- Includes :
  - Dimensions of the main field pole
  - Dimensions of the field coil
  - Current in shunt field winding
  - Resistance of the field coil
  - Dimensions of the field conductor
  - Number of turns in the field coil
  - Losses in the field coil

Dimensions of the main field pole

- Rectangular field pole: area of cross section, length , width and height of pole body
- Cylindrical poles: diameter, area of cross section and height of pole body

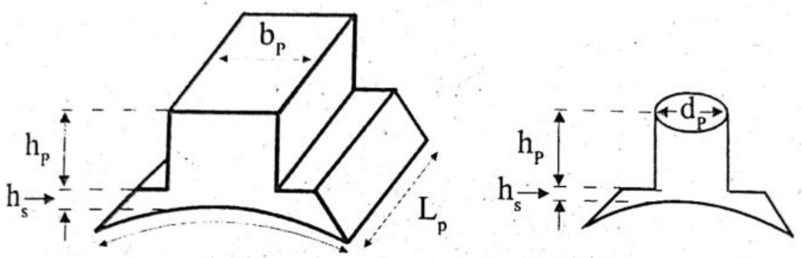


Fig a : Rectangular pole *Fig b : Cylindrical pole*

Dimensions of field pole

Flux in the pole body, $\phi_p = C_l \phi$

C_l- leakage coefficient

Area of pole body, $A_p = \phi_p / B_p$

When circular poles are employed the area of cross-section will be a circle and so the diameter of the pole can be estimated from the equation of circle.

$$\text{Area of pole body, } A_p = \frac{\pi d_p^2}{4}$$

$$\therefore \text{Diameter of pole body, } d_p = \sqrt{\frac{4A_p}{\pi}}$$

When rectangular poles are employed the length of the pole is chosen as 10 to 15 mm less than the length of armature. The reduction in length of pole is to permit end play and to avoid magnetic centering.

Length of pole, $L_p = L - (0.010 \text{ to } 0.015)$

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

Width of the pole, $b_p = \frac{A_p}{L_{pi}}$

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

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

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

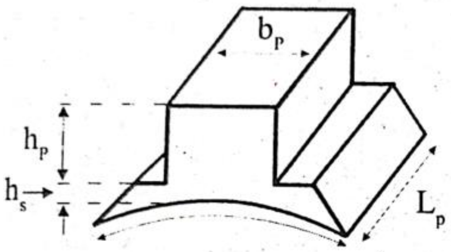


Fig a : Rectangular pole

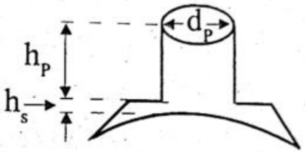


Fig b : Cylindrical pole

Dimensions of field pole

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

DIMENSIONS OF FIELD COIL

- The field coils are former wound and placed on the poles
- Field coils may have rectangular or circular cross-section, depending upon type of poles.
- Dimensions of field coil: depth, height and length of mean turn of field coil

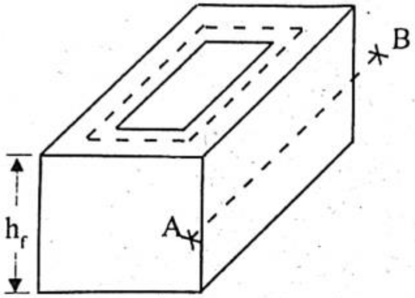


Fig a : *Rectangular field coil*

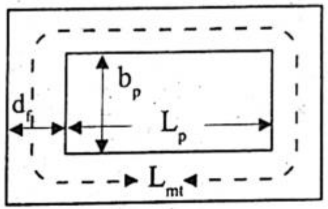


Fig b : *Cross-section of rectangular field coil at AB*

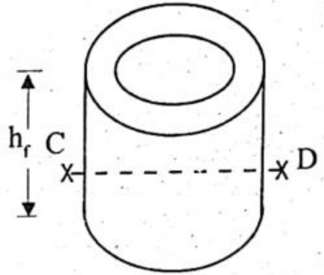


Fig c : *Cylindrical field coil*

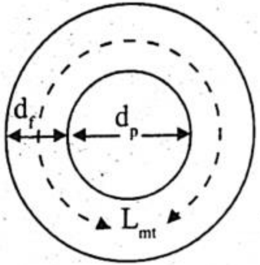


Fig d : *Cross-section of circular field coil at CD*

Dimensions of field coil

- Usually depth of the field coil is assumed and the value depends on diameter of armature
- Height of field coil- h_f
- Number of turns in field coil-T_f
- T_f and h_f Determined in: Power loss in field coil
- The length of mean turn L_{mt} of field coil can be calculated using dimensions of pole and depth of field coil.
- It is length of the turn in centre of field coil

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

For rectangular field coil,

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

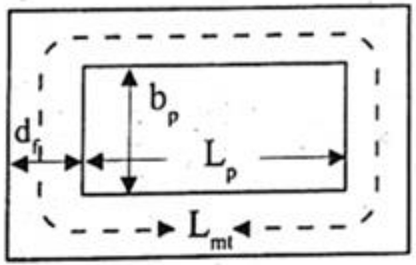
(or) Length of mean turn, $L_{mt} = \frac{L_o + L_i}{2}$

where, L_o = Length of outer most turn

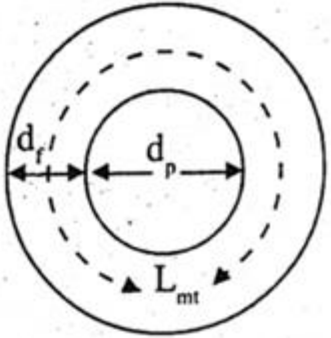
L_i = Length of inner most turn

For cylindrical field coil,

Length of mean turn, $L_{mt} = \pi(d_p + d_f)$



Cross-section of rectangular field coil at AB



Cross-section of circular field coil at CD

Current in shunt field winding

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

Normally the voltage across the shunt field winding is equal to 80 to 85% of rated machine voltage. Because in generators 15 to 20% of rated voltage is absorbed by the field rheostat provided for voltage regulation. In case of motors this allowance depends on the range of speed control.

$$\text{Voltage across each shunt field coil, } E_f = \frac{(0.8 \text{ to } 0.85) \times V}{p}$$

$$\text{The field current, } I_f = \frac{E_f}{R_f}$$

where R_f is the resistance of each field coil.

Resistance of field coil

We know that, $\text{Resistance} = \dfrac{\text{Resistivity} \times \text{Length}}{\text{Area}}$

$$R_f = \frac{\text{Resistivity of copper} \times \text{Length of field coil}}{\text{Area of cross-section of field conductor}}$$

Here, Length of field coil = Length of mean turn × Number of turns in field coil

$$\therefore \text{Resistance of field coil, } R_f = \frac{\rho L_{mt} T_f}{a_f}$$

DIMENSION OF FIELD CONDUCTORS

- The dimensions of field conductor:
  - **Area of cross-section**
  - **Diameter**
- Area of cross section of field conductor can be estimated from the knowledge of field current(I_f) and current density(δ_f)
- The usual range of δ_f: 1.2 to 3.5 A/mm^2

Area of cross-section of field conductor, $a_f = \dfrac{I_f}{\delta_f}$

We know that,

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

$\therefore$ Area of cross-section of field conductor, $a_f = \dfrac{\rho \, L_{mt} \, T_f}{R_f}$

Also, $R_f = \dfrac{E_f}{I_f}$

On substituting for R_f

$$a_f = \frac{\rho \, L_{mt} \, T_f \, I_f}{E_f}$$

We know that, $AT_f = T_f \, I_f$

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

We know that, $AT_f = T_f I_f$

Area of cross - section of field conductor, $a_f = \frac{\rho L_{mt} AT_f}{E_f}$

- **Usually conductors with circular cross-section is used for field winding. Therefore area of cross section is also given by the equation for area of circle.**

Area of cross-section, $a_f = \frac{\pi}{4} d_{fc}^2$

$\therefore$ Diameter of field conductor, $d_{fc} = \sqrt{\frac{4 a_f}{\pi}}$

The conductors used for winding are coated with winding varnish in order to insulate one turn from the other. The diameter of the conductor including the thickness of insulation is necessary to estimate the copper space factor.

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

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

Number of turns in field coil

When the ampere-turns to be developed by the field coil is known the turns can be estimated from the knowledge of field current.

Field ampere turns on load, $AT_{fl} = I_f T_f$

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

POWER LOSS IN FIELD COIL

The power loss in the field coil is copper loss which depends on resistance and current. Heat is developed in the field coil due to this loss and the heat is dissipated through the surface of the coil. If there is no sufficient surface for heat dissipation then heat accumulates, which may lead to damage (or burning) of the coil.

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

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

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

Top surface area of the field coil = $L_{mt}\, d_f$

Bottom surface area of the field coil = $L_{mt}\, d_f$

Total surface area of field coil $\left.\right\}$ $S = L_{mt}(h_f - d_f) + L_{mt}(h_f + d_f) + L_{mt}d_f + L_{mt}d_f$

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

Permissible copper loss in the field coil $\left.\right\}$ $Q_f = S\,q_f$

where q_f is loss dissipated per unit area.

On substituting for S

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

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

On substituting for R_f

$$\text{Actual copper loss} = \frac{E_f^2}{\rho\,L_{mt}\,T_f / a_f} = \frac{E_f^2\,a_f}{\rho\,L_{mt}\,T_f}$$

On equating the permissible copper loss to actual copper loss, we can form an equation with T_f and h_f as variables.

$$\therefore 2\, L_{mt}\, q_f (h_f + d_f) = \frac{E_f^2\, a_f}{\rho\, L_{mt}\, T_f} \qquad \text{———————} \qquad (1)$$

Another equation with T_f and h_f can be formed from the knowledge of conductor area in the field coil as shown below.

$$\left.\begin{array}{l}\text{Conductor area}\\ \text{in field coil}\end{array}\right\} = \text{Number of turns} \times \left(\begin{array}{c}\text{Area of cross - section}\\ \text{of field conductor}\end{array}\right)$$

$$= T_f\, a_f$$

$$\left.\begin{array}{l}\text{Also, conductor}\\ \text{area in field coil}\end{array}\right\} = \text{Copper space factor} \times \left(\begin{array}{c}\text{Area of cross - section}\\ \text{of field coil}\end{array}\right)$$

$$= S_f\, h_f\, d_f$$

On equating the equations

$$T_f a_f = S_f h_f d_f \qquad \text{———————} \qquad (2)$$

The equations (1) and (2) can be solved to estimate h_f and T_f.

DESIGN OF SERIES FIELD WINDING

- Series field winding uses rectangular conductor cross section. Paper or cotton is the most common insulation preferred for conductor.
- Mmf of series field winding at full load usually lies between 15 to 25 percentage more of armature mmf in order to compensate armature reaction.
- Series field winding carries the current same as armature current, so it is designed for less number of turns with large conductor cross section area.
- Less number of turns and large conductor cross section area offers low resistance to a winding.

The step-by-step procedure for design of series field coil is given below.

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

$$\left.\begin{array}{l}\text{Armature ampere turns}\\ \text{at full load (per pole)}\end{array}\right\} = \frac{\begin{array}{c}\text{Current through}\\ \text{a turn}\end{array} \times \begin{array}{c}\text{No.of armature}\\ \text{turns}\end{array}}{\text{Number of poles}}$$

$$= \frac{I_z \times Z/2}{p} = \frac{I_z Z}{2p}$$

Mmf of series field per pole, $AT_{fl} = (1.15 \text{ to } 1.25) AT_a$

For compound machines,

$$\left.\begin{array}{l}\text{Ampere - turns to be}\\ \text{developed by series field coil}\end{array}\right\} AT_{se} = 0.15 \text{ to } 0.25 \times \frac{I_z Z}{2p}$$

For series machines,

$$\left.\begin{array}{l}\text{Ampere - turns to be}\\ \text{developed by series field coil}\end{array}\right\} AT_{se} = 1.15 \text{ to } 1.25 \times \frac{I_z Z}{2p}$$

Step-2 **:** Calculate the number of turns in the series field coil

$$\left.\begin{array}{l}\text{Number of turns}\\ \text{in series field coil}\end{array}\right\} T_{se} = \frac{AT_{se}}{I_{se}} \text{ (rounded to integer)}$$

where, $I_{se} = I_a$ = Current through series field winding at full load.

Step-3 : Determine the area of cross-section of the seires field conductor

$$\left.\begin{array}{l}\text{Area of cross-section}\\ \text{of series field conductor}\end{array}\right\} a_{se} = \frac{I_{se}}{\delta_{se}}$$

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

The current density in chosen as 2 to 2.3 A/mm^2. For low capacity machines circular conductors are used and for higher capacity machines rectangular conductors are used.

Step-4 : Estimate the dimensions of the field coil.

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

Also, conductor area in field coil } = Copper space factor × Height of coil × Depth of coil

$= S_{fse}\, h_{se}\, d_{se}$

where, S_{fse} = Copper space factor for series field coil.

When circular conductors are employed the value of copper space factor is 0.6 to 0.7. When rectangular conductors are employed, the sapce factor depends on thickness and type of insulation.

On equating the two equations for conductor area of field coil we get,

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

$$\therefore \text{Height of field coil, } h_{se} = \frac{T_{se}\, a_{se}}{S_{fse}\, d_{se}}$$

Choose a suitable depth and calculate the height of series field coil using the equation

In case of compound machine, the total height of pole required to accommodate field winding will be sum of the height of shunt field coil and series field coil.

Step-5 : Estimate the resistance of series field coil.

$$\left.\begin{array}{l}\text{Resistance of} \\ \text{series field coil}\end{array}\right\} = \frac{\rho\, L_{mtse} T_{se}}{a_{se}}$$

where, L_{mtse} = Length of mean turn of series field coil.

The length of mean turn of series field coil can be estimated from the dimensions of the pole.

$$\left.\begin{array}{l}\text{Length of mean turn} \\ \text{of series field coil}\end{array}\right\} L_{mtse} = 2(L_p + b_p + 2d_{se})$$

INTERPOLES

- Also known as commutating poles
- Interpoles are small poles placed between main poles.
- The polarity of the interpole must be that of the main pole just ahead for a generator and just behind it for a motor, in the direction of rotation.

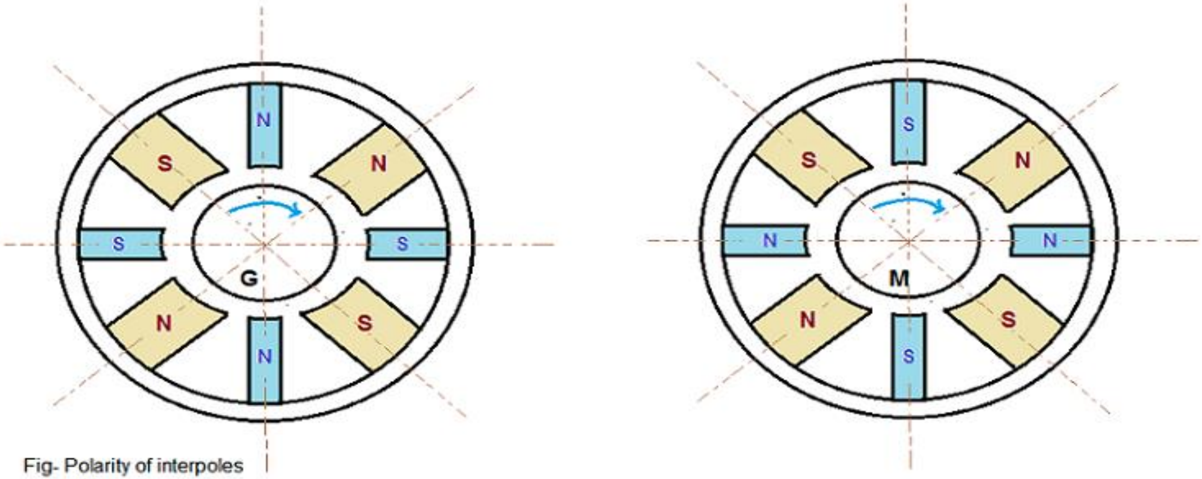


Fig- Polarity of interpoles

- Interpoles are used to counter the effect of armature reaction.
- The winding of the interpole must produce an mmf which is sufficient to neutralize the cross magnetizing armature mmf of interpolar axis and enough more to produce the flux density required to generate rotational voltage in the coil undergoing commutation to cancel the reactance voltage
- Since both the armature voltage and reactance voltage are proportional to the armature current, the interpole winding should be connected in series with the armature for production of neutralizing effect at all conditions of load

Average reactance voltage, $E_{rav} = \frac{4\tau_c \lambda L I_z Z_s}{\tau_c}$

Maximum reactance voltage, $E_{rm} = 1.3 E_{rav}$

Maximum flux density under interpole, $B_{gi} = \frac{E_{rm}}{LV_a}$

mmf required to establish B_{gi}, $A_{gi} = 800000\, B_{gi} K_{gi} l_{gi}$

mmf required for interpole, $AT_i = AT_a + AT_{gi}$

$AT_a = \frac{I_z Z}{2p}$ without compensating winding

$AT_a = \frac{(1-\psi) I_z Z}{2p}$ with compensating winding

No. of turns on each interpole, $T_i = \frac{AT_i}{I_a}$

Area of interpole winding conductor, $a_i = \frac{I_a}{\delta_i}$

T_c – Turns per coil

V_a – Peripheral speed of armature

L – Length of armature.

λ – Specific Permeance.

T_c – Time for commutation.

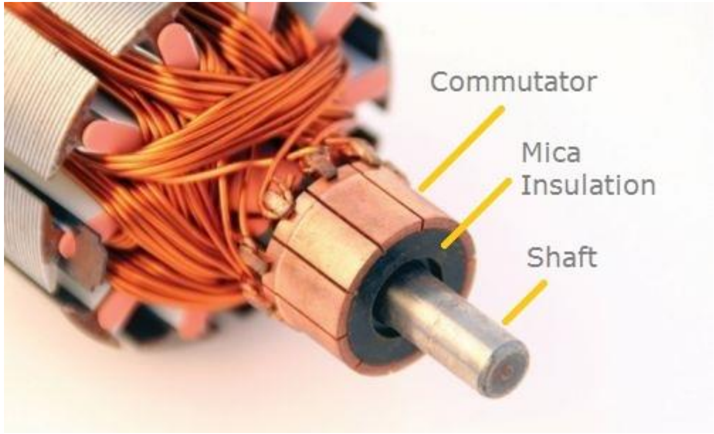
Z_s – No. of conductors in slots

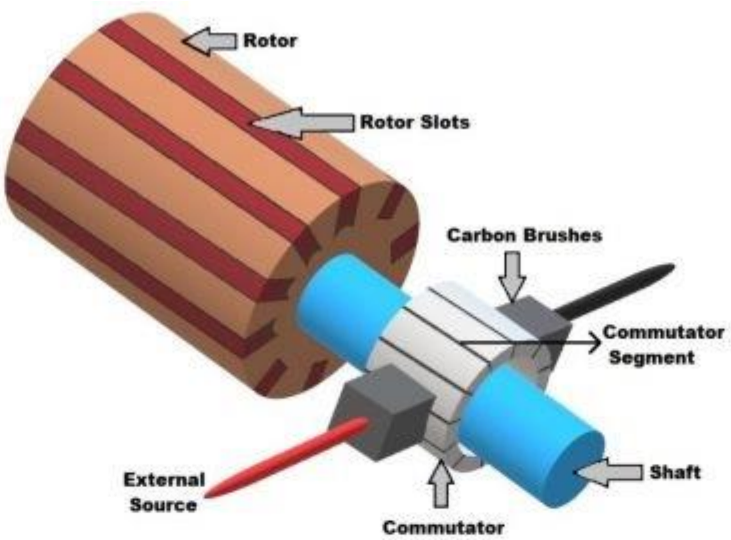
FLUX DENSITY UNDER INTERPOLE

- The interpole must induce voltage in the coil undergoing commutation in a direction to cancel the reactance emf
- Rotational emf produced in the coil by cutting the field under the interpole= $2T_c B_{gi} L_{ip} V_a$
- This voltage must balance the reactance emf E_{rav} in each turn
- $\frac{4T_c \lambda L I_Z Z_S}{T_c} = 2T_c B_{gi} L_{ip} V_a$
- $B_{gi} = 2I_Z Z_S \frac{L}{L_{ip}} \frac{1}{V_a T_c} \lambda$
- **Commutator** in DC machine rectifies alternating current of armature conductor. It is cylindrical shaped structure made of copper bars or segments.
- Commutator segments are separated by insulating material(mica) from one another and connected with armature conductor with the help of riser.

DESIGN OF COMMUTATOR & BRUSHES

- **Commutator** in DC machine rectifies alternating current of armature conductor. It is cylindrical shaped structure made of copper bars or segments.
- Commutator segments are separated by insulating material(mica) from one another and connected with armature conductor with the help of riser.




Rotor
Rotor Slots
Carbon Brushes
Commutator
Segment
Shaft
External
Source
Commutator

NUMBER OF SEGMENTS

- Number of commutator segments is equal to number of coils.
- Number of commutator segment, $C = \frac{1}{2} u S$
  - C- No. of coils
  - u – number of coil sides per slot
  - S-No. of slots
- Minimum number of segment is that which gives a voltage of 15V between segments at no load
- Minimum number of segments $= \frac{Ep}{15}$
  - E- Generated emf
  - p- no. of poles

COMMUTATOR DIAMETER

- Diameter of commutator is taken as 60 to 80 percentage of armature diameter.
- Commutator diameter, ***Dc* = (0.6 to 0.8)*D***
- Commutator diameter varies from :
  - 62% for 350/700 V,
  - 68% for 200/250 V
  - 75% for 100/125 V machine
- Larger diameter being necessary on heavy current(low voltage) machines because of higher mechanical stresses and heating

- In order to avoid ionization of the skin of air at commutator surface, **peripheral voltage gradient around commutator is limited to 3 V/mm**.
- Hence, commutator diameter is selected with regards of peripheral speed and thickness of segment.

Peripheral speed:

- Commutator peripheral speed is generally kept **below15m/s**
- Higher peripheral speeds upto 30m/s are used but should be avoided wherever possible
- Higher commutator peripheral speeds generally leads to commutation difficulties

Commutator segment pitch:

- Thickness of commutator segment at commutator surface **should not be less than 3 mm.**
- If thickness of mica is about 0.8mm ,then minimum segment pitch is approximately 4 mm.
- Pitch of segment, $\beta_c = \frac{\pi D_c}{C}$

LENGTH OF COMMUTATOR

- Length of commutator depends upon the space required by the brushes and upon the surface required to dissipate the heat generated by commutator losses

DIMENSIONS OF BRUSHES

- Thickness of brushes has great influence on the commutation condition
- Thickness of the brush t_c and commutator segment pitch $\beta_c$determine the width of the commutating zone and number of coils undergoing commutation at a time
- Thickness of brush should cover 2 to 3 commutator segment for good design.

- Current carried by each brush spindle= $\frac{2I_a}{p}$

$$\text{Thickness of each brush}, t_b = (2 \text{ to } 3)\beta_c$$

- Total brush contact area per spindle, $A_b = \frac{I_b}{\delta_b}$
- $A_b = \frac{2I_a}{p\delta_b}$
- δ_b - current density in brushes

The area of each individual brush should be chosen such that it does not carry more than 70 A. Hence the number of brushes in a spindle, n_b is selected such that each brush does not carry more than 70 A.

Let a_b = Contact area of each brush

n_b = Number of brushes per spindle

Now, contact area of brushes in a spindle, $A_b = n_b a_b$

Also, $a_b = w_b t_b$

$\therefore A_b = n_b w_b t_b$

Usually, the thickness of brush, $t_b = (2 \text{ to } 3) \times \beta_c$

$$\therefore \text{Width of brush, } w_b = \frac{A_b}{n_b t_b} = \frac{a_b}{t_b}$$

The length of the commutator depends on the space required for mounting the brushes and to dissipate the heat generated by the commutator losses.

Length of commutator, $L_c = n_b (w_b + C_b) + C_1 + C_2$

C_b = Clearance between the brushes (usually 5 mm)

C_1 = Clearance allowed for staggering the brushes (10 mm for small machine and 30 mm for large machine)

C_2 = Clearance for allowing end play (usually 10 to 25 mm).

The losses at the commutator are the brush contact losses and the brush friction losses. The brush contact loss depends on material, condition and quality of commutation obtained. Hence it is difficult to predetermine accurately the brush contact losses. The brush contact drop V_b is independent of load current.

The brush friction loss can be calculated from the formula,

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

P_b = Brush contact pressure on commutator, N/m^2

A_B = Total contact area of all brushes, m^2

A_B = $p A_b$ for lap winding ; μ = Coefficient of friction

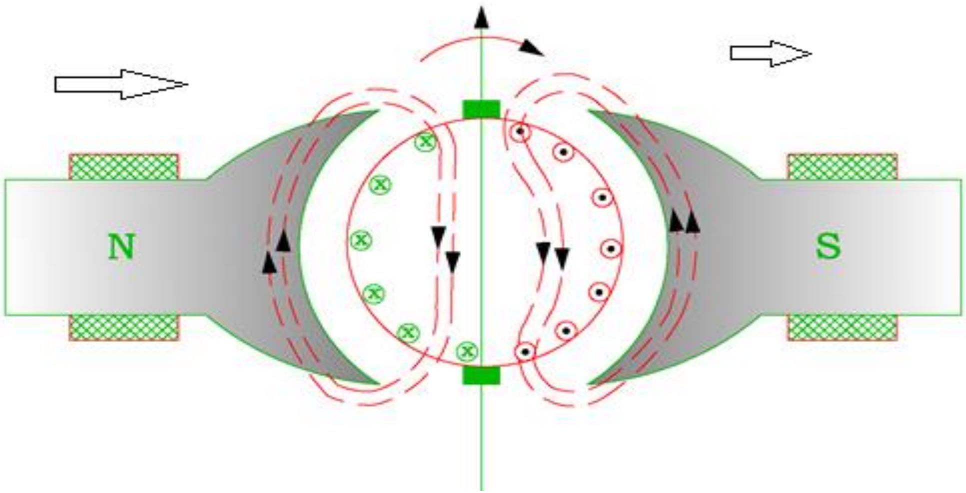
A_B = $2A_b$ for wave winding ; V_c = Peripheral speed of commutator, m / sec.

Properties of Brush Materials

Type of material	Brush contact drop in V	Current density in A/mm^2	Pressure in kN/m^2	Commutator speed in m/sec	Co-efficient of friction
Natural graphite	0.7 - 1.2	0.1	14	50 - 60	0.1 - 0.2
Hard carbon	0.7 - 1.8	0.065-0.085	14 - 20	20 - 30	0.15 - 0.25
Electro--graphite	0.7 - 1.8	0.085-0.11	18 - 21	30 - 60	0.1 - 0.2
Metal graphite	0.4 - 0.7	0.1 - 0.2	18 - 21	20 - 30	0.1 - 0.2

COMPENSATING WINDING

- Compensating windings are used to neutralize the effect of armature reaction
- These windings are of concentric type and are housed in axial slots in the pole faces
- The conductors of this winding carry currents in opposite direction to that of the adjacent armature conductors in order to nullify the effect of armature mmf
- Compensating winding is connected in series with armature winding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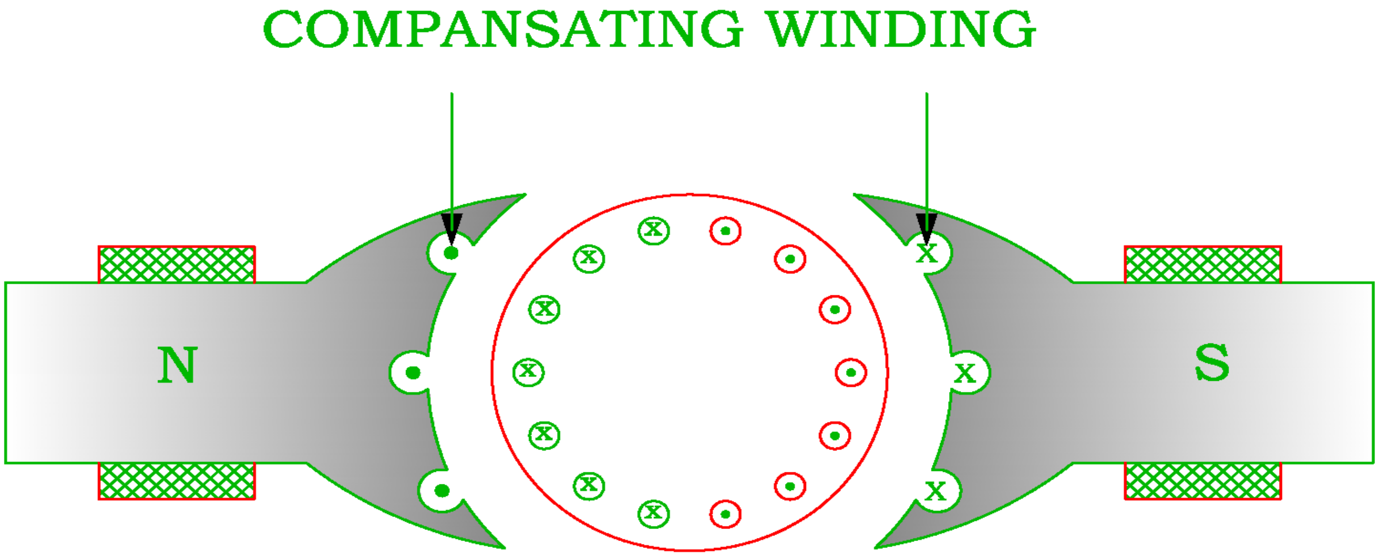


FIG D : COMPENSATING WINDING

- **In order to obtain perfect compensation of armature mmf under the pole shoe, it is necessary that compensating winding ampere conductors are equal to the total ampere conductors under the pole shoe**
- **Compensating winding mmf per pole**
- $AT_C = \frac{Pole\ Arc}{Pole\ Pitch} \times armature\ mmf\ per\ pole$
- $AT_C = \psi\, AT_a$

THANK YOU

MODULE 4

DESIGN OF SYNCHRONOUS MACHINE

Output Equation

Let

V_{ph} = phase voltage ;

I_{ph} = phase current

Z_{ph} = no of conductors/phase;

T_{ph} = no of turns/phase

N_s = Synchronous speed in rpm;

n_s = synchronous speed in rps

p = no of poles ;

ac = Specific electric loading

Φ= air gap flux/pole;

B_{av} = Average flux density

K_w = winding factor ;

D = Diameter of the stator;

L = Gross core length

C_o = Output coefficient;

OUTPUT EQUATION OF 3ϕ SYNCHRONOUS MACHINE

Output of machine, $Q = 3 V_{ph} I_{ph} \times 10^{-3}$ kVA

Assuming induced emf, $E_{ph} = V_{ph}$

Output of machine, $Q = 3 E_{ph} I_{ph} \times 10^{-3}$ kVA

Induced emf, $E_{ph} = 4.44 f \phi T_{ph} K_w$

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

$= 3 \times 4.44 \left(\frac{p n_s}{2}\right) \phi T_{ph} K_w I_z \times 10^{-3}$

$f = \frac{p n_s}{2}$

$I_z = I_{ph}$ [as there is only one circuit per phase]

$$= 3 \times 2.22\, p n_s \phi\, T_{ph} K_w I_z \times 10^{-3}$$

$$= 1.11 \times 6\, p n_s \phi\, T_{ph} K_w I_z \times 10^{-3}$$

$$= 1.11 \times (6T_{ph})(p\phi) K_w n_s I_z \times 10^{-3}$$

$$= 1.11 \times Z (p\phi) K_w n_s I_z \times 10^{-3}$$

$$= 1.11\, K_w (p\phi)(I_z Z) n_s \times 10^{-3}$$

$$= 1.11\, K_w (\pi D L B_{av})(\pi D ac) n_s \times 10^{-3}$$

$$= (1.11\, \pi^2 B_{av} ac\, K_w \times 10^{-3}) D^2 L n_s$$

$$= (11\, B_{av} ac\, K_w \times 10^{-3}) D^2 L n_s$$

$$= C_o D^2 L n_s$$

$$\boxed{Q = C_o D^2 L n_s}$$

where C_o - output coefficient

$$C_o = 11 B_{av} ac K_w \times 10^{-3}$$

Total no of conductors

Z = no of phases $\times 2T_{ph}$

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

$Z = 6 T_{ph}$

Specific magnetic Loading

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

$$p\phi = B_{av} \pi D L$$

Specific electric Loading

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

$$I_z Z = \pi D ac$$

SPECIFIC MAGNETIC LOADING(B_{av})

The average flux density over the air gap of a machine is known as specific magnetic loading

$$B_{av} = \frac{Total\ flux\ around\ the\ air\ gap}{Area\ of\ flux\ path\ at\ the\ air\ gap}$$

$$\boxed{B_{av} = \frac{P\emptyset}{\pi D L} = \frac{\emptyset}{\tau L} \quad where\ \tau = \frac{\pi D}{P}}$$

SPECIFIC ELECTRIC LOADING(ac)

The number of stator ampere conductors per metre of stator periphery at the air gap is known as specific electric loading

$$ac = \frac{Total\ stator\ ampere\ conductors}{Stator\ periphery\ at\ air\ gap}$$

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

CHOICE OF SPECIFIC MAGNETIC LOADING

- **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.
- **Voltage**: When the machine is designed for higher voltage, space occupied by the insulation becomes more thus making the teeth smaller and hence lower value of gap density should be used.
- **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.
- **Stability**: The maximum power output of a machine under steady state condition is inversely proportional to synchronous reactance. If higher value of flux density is used, the flux per pole is large and it leads to smaller number of turns per phase in armature winding. This results in reduced value of synchronous reactance and hence increased value of power and hence increased steady state stability.
- **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.

Following are the usual Bav assumed : Salient pole machine : 0.52 to 0.65 Wb/m^2
Cylindrical rotor machine : 0.54 to 0.65 Wb/m^2

CHOICE OF SPECIFIC ELECTRIC LOADING

Following are the some of the factors which influence the choice of specific electric loadings:

- **Copper loss**: Higher the value of 'ac', larger will be the number of armature conductors which results in higher copper loss. This will result in higher temperature rise and reduction in efficiency.
- **Voltage**: A higher value of 'ac' can be used for low voltage machines since the space required for the insulation will be smaller.
- **Synchronous reactance**: High value of 'ac' 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.

- ❖ **Stray load losses**: With increased value of 'ac' stray load losses will increase.

The usual values of 'ac': Salient pole machines : 20000 to 40000 amp-cond/m

Turbo machines : 50000 to 75000 amp-cond/m

DESIGN OF SALIENT POLE MACHINE

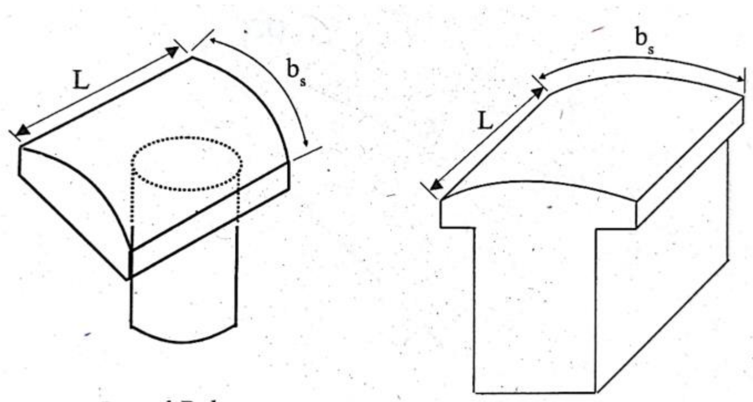
MAIN DIMENSIONS

- ❖ The main dimensions of salient pole machines are D and L.
- ❖ **D depends on:**
    1. **Type of poles used**
    2. **Permissible peripheral speed**
- ❖ 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($\frac{b_s}{\tau}$) may be assumed varying between 0.6 to 0.7 .
- ❖ Under these conditions it is possible to use round poles with square pole shoes
- ❖ Length of pole= width of pole shoe (L = b_s)
- ❖ Pole arc may be taken as approximately equal to axial length of the stator core.
- ❖ L/ τ = 0.6 to 0.7



Round Pole *Rectangular Pole*

Rectangular poles

- ❖ The ratio of axial length to pole pitch may be assumed varying between 1 to 5.
- ❖ Axial length of the core/ pole pitch = L/ τ = 1 to 5
- ❖ This ratio should not exceed 3 for normal machines otherwise the design of field system becomes uneconomical.

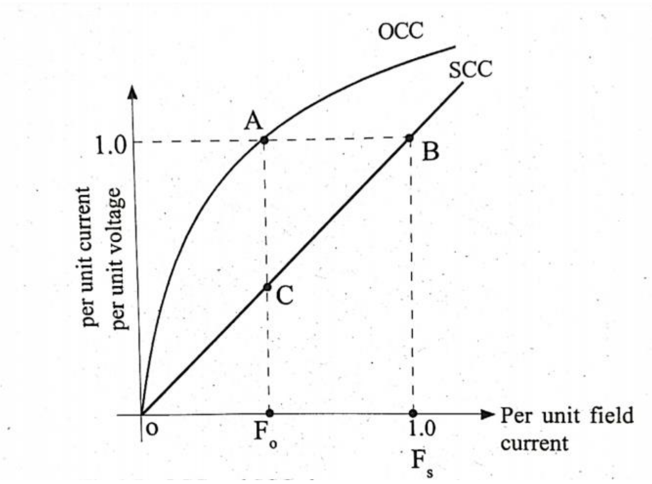
- Using the above relations D and L can be separated.
- However once these values are obtained diameter of the machine must satisfy the limiting value of peripheral speed so that the rotor can withstand centrifugal forces produced.
- **Limiting values of peripheral speeds are as follows:**

- ❖ **Bolted pole construction = 50 m/s**
- ❖ **Dove tail and T head pole construction = 80 m/s**
- ❖

SHORT CIRCUIT RATIO

- ❖ The **Short Circuit Ratio** (SCR) of a **synchronous machine** is defined as the **ratio** of the field current required to generate rated voltage on an **open circuit** to the field current required to circulate rated armature current on **short circuit**.

$$SCR= \frac{\textit{Field current required to produce rated voltage on open circuit}}{\textit{Field current required to circulate rated current at short circuit}}$$



$$SCR = \frac{OF_o}{OF_s}$$

OF_o = Per unit field current required to develop rated voltage on open circuit.
OF_s = Per unit field current required to develop rated current on short circuit.

$$\therefore SCR = \frac{OF_o}{OF_s} = \frac{CF_o}{BF_s} = \frac{CF_o}{AF_o}$$

$$\therefore SCR = \frac{CF_o}{AF_o} = \frac{1}{AF_o / CF_o} = \frac{1}{\dfrac{\text{pu volt on open circuit}}{\text{pu SC current corresponding to pu volt}}}$$

$$\text{Direct axis reactance, } X_d = \frac{\text{pu volt}}{\text{pu SC current}}$$

❖ **SCR=$\frac{1}{X_d}$**

❖ *X_d- Synchronous reactance*

❖ *SCR is the reciprocal of synchronous reactance (X_d) in per unit.*

- For **turbo-alternator** SCR is normally between **0.5 to 0.7**
- For **salient pole hydro electric generators** SCR varies from **1 to 1.5**

Effect of SCR on Machine performance

1. **Voltage regulation**: A low value of SCR means that the synchronous reactance has a high value resulting in to poor voltage regulation.
2. **Short circuit current:** A small value of SCR means a large value of Xd which will limit the short circuit current during fault conditions.
3. **Parallel operation** : A machine with low value of SCR means a large value of Xd giving a small value of synchronizing power. Such a machine have problem during parallel operation.
4. **Stability**: A machine with low value of SCR. i.e. higher value of Xd , will lead to lower synchronizing power and thus giving a lower stability limit.
5. **Self excitation**: Machine feeding with long transmission lines should not be designed with a small SCR(high X_d) as this would lead to large voltages on open circuit produced by self excitation owing to large capacitive currents drawn by the transmission lines

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.

❖ A large air-gap offers a large reluctance to the path of flux produced by the armature mmf and thus reduces the effect of armature reaction.

❖ This result in small value of synchronous reactance and a high value of SCR.

Increase in air-gap length

Advantages:

- Stability: Higher value of stability limit
- Regulation: Smaller value of inherent regulation
- Synchronizing power: Higher value of synchronizing power
- Cooling: Better cooling
- Noise: Reduction in noise
- Magnetic pull: Smaller value of unbalanced magnetic pull

Disadvantages:

- Field mmf: Larger value of field mmf is required
- Size: Larger diameter and hence larger size

- Magnetic leakage: Increased magnetic leakage
- Weight of copper: Higher weight of copper in the field winding
- Cost: Increase over all cost.

The approximate value of air gap length can be expressed in terms of pole pitch.

For salient pole alternators: $\frac{l_g}{\tau}$ = 0.01 to 0.015

For turbo alternators: $\frac{l_g}{\tau}$ = 0.02 to 0.025

Synchronous motors designed with maximum output 1.5 times rated output, $\frac{l_g}{\tau}$= 0.02

Estimation of length of air gap

- Length of the air gap is usually estimated based on the ampere turns required for the air gap.
- Armature ampere turns per pole required AT_a =2.7I_{ph} T_{ph}Kw /p
  - Where Tph - Turns per phase,
  - Iph - Phase current,
  - Kw - winding factor,
  - p - pairs of poles
- No load field ampere turns per pole AT_{fo} = SCR x Armature ampere turns per pole
- **AT_{fo} = SCR x AT_a**
- Ampere turns required for the air gap will be approximately equal to 80% of the no load field ampere turns per pole.
- Mmf for air gap is also equal to $800000 B_g K_g l_g$
- **0.8 AT_{fo} = 800000 $B_g K_g l_g$**

l_g = 0.8 AT_{fo} /800000 $B_g K_g$

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

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.

Selection of number of slots

Following factors are considered for selection of number of slots.

- **Balanced winding**:- The number of slots are so selected that a balanced 3-phase winding is obtained. Unbalance winding will leads to generation of space harmonics and over heating.

- **Tooth flux density**:- selection of large number of slots will lead to narrower teeth resulting in to increased tooth flux density beyond permissible limits.
- **Leakage reactance**:- With less number of slots, the conductors are nearer leading to increased leakage flux and thereby increased leakage reactance.
- **Tooth ripples**:- With large number of slots tooth ripples and therefore pulsation loss decreases.
- **Temperature rise** :- Less number of slots will lead to crowding of conductors, disturbance in air circulation and hence developing high internal temperature.
- **Cost**: Less number of slots result in saving in labour because of less number of coils to wind, insulate, place in to slots and connect.

- Slot loading must be less than 1500 ac/slot
- Slot pitch(y_s) must be with in the following limitations
    - Low voltage machines ≤ 25 mm
    - Medium voltage machines(or low voltage machine) up to 6kV ≤ 40 mm
    - High voltage machines up to 15 kV ≤ 60 mm
- The stator slot pitch for large hydro-electric generators varies between 50mm and 90mm.
- Considering all the above points number of **slots per pole per phase** for salient pole machines may be taken as **2 to 4**

TURNS PER PHASE

- Turns per phase can be calculated from emf equation of the alternator.
- Induced emf E_{ph}= 4.44 f Φ $T_{ph} K_w$
- Hence turns per phase $\boldsymbol{T_{ph} = \frac{E_{ph}}{4.44\ f\ \Phi\ K_w}}$

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

- This equation is applicable when all the turns of a phase are connected in series.
    - E_{ph} = induced emf per phase
    - T_{ph} = no of turns/phase
    - K_w = winding factor may assumed as 0.955
- If there are 'a' parallel paths per phase: E_{ph}= 4.44 f Φ $\frac{T_{ph}}{a} K_w$
- $\boldsymbol{T_{ph} = \frac{E_{ph} \cdot a}{4.44\ f\ \Phi\ K_w}}$

CONDUCTOR SECTION

- Current per phase, $I_Z = I_{ph} = \frac{(\text{kVA x 1000})}{3 * \text{Eph}}$
- The conductor current Iz = Iph, when all the turns per phase are connected in series.
- But Iz = Iph/a , if there are 'a' number of parallel paths per phase.

- Sectional area of the stator conductor $a_s = \frac{I_Z}{\delta_a}$
- $a_s = \frac{I_s}{\delta_s}$
    - where δa is the current density in stator windings

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 A/mm^2

DESIGN OF STATOR 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 120˚ 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

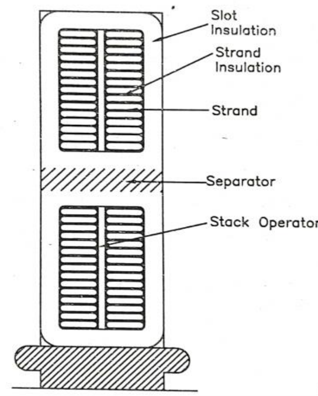
- **Disadvantages:**

(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

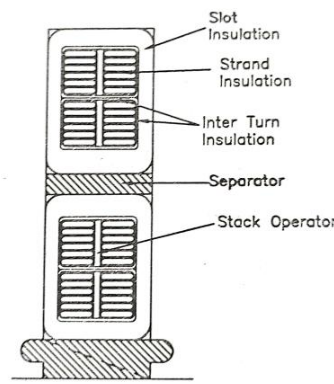
Single turn bar windings

- The cross section of the conductors is quite large because of larger current.
- Hence in order to eliminate the eddy current loss in the conductors, stator conductors are subdivided into many parts.
- The subdivision is achieved by laying a number of bare copper strips flat wise in the slot
- Each slot of the stator conductor consists of two stranded conductors.
- Each conductor consists of two vertical stacks of copper laminations insulated with either asbestos or glass
- The dimensions of individual strands are selected based on electrical considerations and the manufacturing requirements. Normally the width of the strands is assumed between 4 mm to 7 mm. The depth of the strands is limited based on the consideration of eddy current losses and hence it should not exceed 3mm. The various strand of the bar are transposed in such a way as to minimize the circulating current loss.



Multi turn coils

- In addition to insulation between individual strands, insulation between turns has to be provided.
- Multi turn coils are former wound.
- These coils are made up of insulated high conductivity copper conductors.
- Mica paper tape insulations are provided for the portion of coils in the slot and varnished mica tape or cotton tape insulation is provide on the over hang portion.
- The thickness of insulation is decided based on the voltage rating of the machine.
- Multi turn coils are usually arranged in double layer windings in slots



Stator coils

- Two types of coils are employed in the stator windings of alternators. They are **single turn bar coils and multi turn coils**.
- Comparisons of the two types of coils are as follows

(i) Multi turn coil winding allows greater flexibility in the choice of number of slots than single turn bar coils.
(ii) Multi turn coils are former wound or machine wound where as the single turn coils are hand made.
(iii) Bending of top coils is involved in multi turn coils where as such bends are not required in single turn coils.
(iv) Replacing of multi turn coils difficult compared to single turn coils.
(v) Machine made multi turn coils are cheaper than hand made single turn coils.
(vi) End connection of multi turn coils are easier than soldering of single turn coils.
(vii) Full transposition of the strands of the single turn coils are required to eliminate the eddy current loss.
(viii) Each turn of the multi turn winding is to be properly insulated thus increasing the amount of insulation and reducing the space available for the copper in the slot.

- From the above discussion it can be concluded that multi turn coils are to be used to reduce the cost of the machine. In case of large generators where the stator current exceeds 1500 amps single turn coils are employed.

STATOR SLOT DIMENSIONS

- Because parallel sided slots are used the teeth are tapered having minimum width at the gap surface.
- The flux density in teeth at the air gap surface at no load does not exceed about 1.7 to 1.8 Wb/m2 .

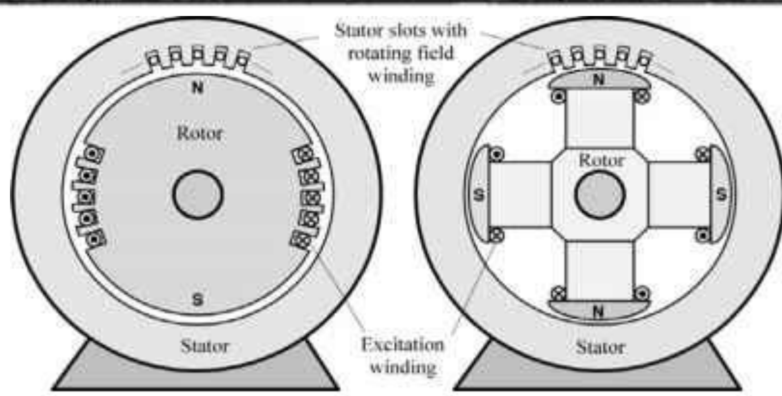
$$w_{t(\min)} = \frac{\emptyset}{\psi \frac{S_s}{p} L_i * 1.8}$$

- Where ψ = ratio of pole arc to pole pitch The depth of the slot ds is now determined by the space requirement for copper and insulation. The depth of slot is normally about 3 times the width.
- The length of mean turn: **Lmt = 2L + 2.5 τ_p + 0.06 kV + 0.2 m**
- Kv- voltage of machine in kilovolt
- Width of the slot = slot pitch – tooth width
- 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

STATOR CORE

- The value of depth of core, d_c can be calculated by assuming suitable value of density B_c. The value of flux density in the armature core of salient pole machines lies between 1.0 to 1.2 Wb/m^2.
- Depth of armature core, $d_c = \frac{\Phi}{2L_iB_c}$
- Outer diameter of stator, D_o=D+ 2(d_s+d_c)

Sr. No.	Salient Pole Type	Smooth Cylindrical Type
1.	Poles are projecting out from the surface.	Unslotted portion of the cylinder acts as poles hence poles are non-projecting.
2.	Air gap is non-uniform.	Air gap is uniform due to smooth cylindrical periphery.
3.	Diameter is high and axial length is small.	Small diameter and large axial length is the feature.
4.	Mechanically weak.	Mechanically robust.
5.	Preferred for low speed alternators.	Preferred for high speed alternators i.e. for turboalternators.
6.	Prime mover used are water turbines, I.C. engines.	Prime movers used are steam turbines, electric motors.
7.	For same size, the rating is smaller than cylindrical type.	For same size, rating is higher than salient pole type.
8.	Separate damper winding is provided.	Separate damper winding is not necessary.



Cylindrical Rotor **Salient Pole Rotor**

DESIGN OF FIELD SYSTEM

1) SALIENT POLE ALTERNATOR (WATER WHEEL ALTERNATOR)

i) Selection of area of pole.

Leakage Coefficient

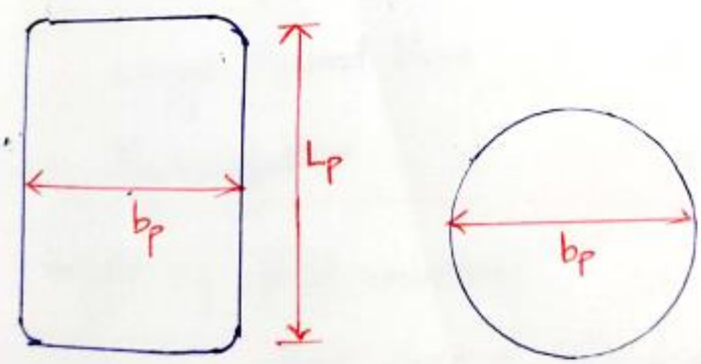
$$C_L = \frac{\text{Total flux in pole body}}{\text{Useful flux}} = \frac{\phi_p}{\phi}$$

$$\phi_p = C_L \phi$$

Cross section area of pole body

$$A_p = \frac{\phi_p}{B_p}$$

B_p - flux density in pole body $= 1.5$ to $1.7\ Wb/m^2$



Rectangular Pole | Round Pole.

$A_p = 0.98 L_p \cdot b_p$

L_p - Length of pole

b_p - Breadth of pole

$A_p = \frac{\pi}{4} b_p^2$

b_p – diameter of pole.

ii) Pole Height

a) Total copper area of field winding

$$= \frac{\text{field mmf for full load}}{\text{field current Density}}$$

$$= \frac{AT_{fl}}{\delta_f}$$

δ_f - field current density (3 to 4 A/mm^2)

Space required for field winding

$$= \frac{\text{Cu Area}}{\text{Space factor}}$$

Type of conductor	Space factor
Small Round Wire	0.4
Large Round Wire	0.65
Rectangular	0.75

Height of field winding =

$$\frac{\text{Total Area of field winding}}{\text{Depth of field winding } (d_f)}$$

Pole pitch (mm)	d_f (mm)
100	25
200	35
400	45

Alternatively

ii) Height of field winding

$$h_f = \frac{AT_{fL}}{10^4 \sqrt{S_f \cdot d_f \cdot q_f}}$$

S_f - Cu space factor

d_f - depth of winding

q_f - Loss per unit surface (W/m^2)

iii) Radial length of pole

$$h_{pl} = h_f + h_1 + 0.02\ m$$

h_1 - Height of pole shoe

$h_p = h_f + 0.02$

h_p - Height of pole body

$\frac{h_{pl}}{\tau} = 0.3$ to 1.5

iv) Cooling coefficient for rotating field coils

$$c = \frac{0.08 \text{ to } 0.12}{1 + 0.1 V_a}$$

Specific loss dissipation, $\lambda = \frac{1}{c} = \frac{1 + 0.1 V_a}{0.08 \text{ to } 0.12}$ $W/m^2\text{-}^\circ C$

Loss dissipated per unit surface

$$q_f = \lambda\theta = \left[\frac{1+0.1V_a}{0.08 \text{ to } 0.12}\right]\theta \quad W/m^2$$

θ - permissible temp. rise.

Design of damper winding

Total area of damper bar per pole

$$A_d = 0.2\, ac\, \tau / \delta_d$$

δ_d - current density in the bars.

Pole arc = No. of bars per pole $\times y_s \times 0.8$

Length of each damper bar

$L_d = 1.1L$ for small machine

$= L + 0.1m$ for large machine.

Cross section of each damper bar

$$a_d = \frac{\text{Total area of bars per pole}}{\text{No. of damper bars per pole}}$$

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

In case of circular bars

$$a_d = \frac{\pi}{4} d_d^2$$

d_d - diameter of damper bar.

Area of each ring short circuiting the bar.

$$A_{ring} = (0.8 \text{ to } 1)\, A_d$$

Height of pole shoe (h_s)

$$h_s = 2d_d$$

h_s - Height sufficient to accomodate damper wdg.

Design of field Winding:

Procedure:

Length of mean turn of field conductor.

$$L_{mtf} = 2L_m + \pi(b_p + 0.01 + d_f)$$

$$L_m = 0.9L$$

1) Voltage across each field coil

$$E_f = \frac{(0.8 \text{ to } 0.85)\, V_e}{P}$$

V_e – Exciter Vtg.

P – No. of poles

2) Height of field coil

$$h_f = h_{pl} - h_1 - \text{space for flanges}$$

h_{pl} – Ht. of pole

h_1 – Ht. of pole shoe.

3) Area of field conductor

field mmf per pole at full load

$$AT_{fl} = I_f T_f$$

$$E_f = \frac{I_f T_f \rho L_{mtf}}{a_f} = \frac{AT_{fl} \rho L_{mtf}}{a_f}$$

Area of field conductor

$$a_f = \frac{AT_{fl} \rho L_{mtf}}{E_f}$$

5) field current = Current density × Area of conductor

$$I_f = \delta_f \cdot a_f$$

δ_f – field current density = 3 to 4 A/mm²

6) No. of turns, $T_f = \frac{AT_{fL}}{I_f}$ $\qquad AT_{fL} = I_f T_f$

7) Resistance of field winding

$$R_f = \frac{\rho L_{mtf} T_f}{a_f}$$

8) Copper loss in each field coil

$$Q_f = I_f^2 R_f$$
$$= I_f^2 \cdot \frac{\rho L_{mtf} T_f}{a_f}$$

9) Temperature rise in field winding

$$\theta = \frac{Q_f C_f}{S}$$

C_f - Cooling coeff. to rotating field coil

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

S – Dissipating surface of coil

h_f – Ht. of field coil

d_f – depth of field coil

$$C_f = \frac{0.08 \text{ to } 0.12}{1 + 0.1 V_a}$$

ROTOR DESIGN (TURBO ALTERNATORS)

Procedure for rotor winding design.

1) full load mmf $AT_{fL} = 2AT_a$

$$AT_a = 2.7\, I_{ph} T_{ph} K_w / p$$

2) Voltage across each field coil, $E_f = \frac{(0.8 \text{ to } 0.85) V_e}{p}$

3) Length of mean turn of field winding

$$L_{mtf} = 2L + 2.3\tau + 0.24$$

τ - effective span of coil.

4)
$$E_f = I_f R_f$$
$$= I_f \frac{\rho L_{mtf} T_f}{a_f} = AT_{fL} \frac{\rho L_{mtf}}{a_f}$$

$AT_{fL} = I_f T_f$

I_f - Field Current

T_f - No. of turns in each coil

Area of field conductor

$$a_f = \frac{AT_{fL} \rho L_{mtf}}{E_f}$$

5) Total area of field conductor $= \frac{2pAT_{fL}}{\delta_f}$

6) No. of field conductors $= \frac{2pAT_{fL}}{\delta_f a_f}$

conductor per slot $= \frac{2pAT_{fL}}{\delta_f a_f S_r}$

S_r - No of wound slots in rotor

COOLING OF A SYNCHRONOUS GENERATOR

Cooling of a Synchronous Generator is very essential. Natural cooling is not adequate to dissipate the great amount of heat produced in the alternators. In the forced air cooling system, air is forced into the alternator so that a greater quantity of air is passed over the surface and a large amount of heat is removed. The Closed circuit ventilation system is used for better cooling of the synchronous generator. In the closed system clean, hot air from the alternator is cooled by a water-cooled heat exchanger and forced through the alternator by fans.

Ducts are provided in the stator and the rotor cores and also in the field coils of the generators or machine for increasing the surface area which is in contact with the cooling air. Depending upon the direction of the air flow these ducts can be radial or axial

1) RADIAL FLOW VENTILATION SYSTEM

In the **radial flow ventilation** system, the cooling air enters the ducts through stator by way of the air gap and passes radially to the back of the stator from where it is removed.

Advantages of Radial Ventilation

- The energy loss for ventilation is minimum.
- The system is applicable both to the small and large machine.

Limitations of Radial Ventilation

- It makes the machine less compact since ventilating ducts occupy about 20 percent of the armature length.
- The heat dissipation is less as compared to the other system. In certain cases, the system becomes unstable because of the quantity of cooling air flowing through the machine.

2) AXIAL FLOW VENTILATION SYSTEM

In the method air is forced in the Axial direction through passages formed by the holes in the stator and rotor.It is highly effective, except for machines with considerable axial length. The disadvantage of axial ventilation is nonuniform heat transfer. The air outlet part of the machine is cooled less because the air in passing through the axial ducts has time to become heated.

3) CIRCUMFERENTIAL VENTILATION

In this method air is supplied at one or more points on the outer periphery of the stator core and forced circumferentially through the ducts between the laminations to suitable outlets. In this method, the duct area can be increased.

In some cases, this method is combined with the radial flow system, but the resultant interference in the two streams of air has to be avoided. For this, the alternating radial ducts are closed on the outer surface.

Requirements of Cooling Air

The air should be **clean and free from dust**. These will clog the ducts to reduce area which results in reducing heat transfer by conduction. Air filters and cheese cloth filters are used.

Sometimes air has to be washed in a spray chamber. In most cases air is cooled by water coolers and used again.

Limitations of Air Cooling

For large capacity machines, the sizes of the fans required for circulation of air increases and required considerable power. Thus, auxiliary equipment are required, which are expensive.

There is an optimum rating of the machine beyond which air cooling will not be able to keep the temperature within safe limits.

4) HYDROGEN COOLING OF A SYNCHRONOUS GENERATOR

Hydrogen gas is used as a cooling medium in the generator casing because of its superior cooling properties. Certain mixtures of hydrogen and air are explosive. The explosion may take place with a range of 6 percent hydrogen and 94 percent air up to 71 percent hydrogen and 29 percent air. When there is more than 71 percent hydrogen, the mixture is not combustible. In practice 9:1 ratio of hydrogen to air is used in very large turbo alternators.

To prevent an explosive mixture of hydrogen and air from occurring in the generator, the hydrogen gas is maintained at a pressure above the atmosphere to prevent inward seepage of contaminating the air. Hydrogen cooling at 1, 2, and three times the atmospheric pressure can raise the rating of the generator by 15,30 and 40 percent respectively above its cooled air rating.

Hydrogen cooling requires completely **seated circulating system**. Special oil seated glands are used between shaft and casing. Since oil absorbs both hydrogen leaking out and air leaking in, it is purified periodically.

The hydrogen gas is circulated by blowers and fans through the rotor and stator, and then it is passed over cooling coils inside the casing. The coils carry oil or water to extract heat from the circulating hydrogen.

Hydrogen cooling increases the overall full load efficiency of the generator by about 1 percent but increases the generator capacity by about 25 percent of the generator of the same physical size using air.

ADVANTAGES OF HYDROGEN COOLING OVER AIR COOLING

Cooling

Hydrogen gas has a higher thermal conductivity. It has 1.5 times heat transfer capability as compared with the air. Therefore, cooling with hydrogen gas is faster than cooling with air.

Windage, Efficiency and Noise

The density of hydrogen is about 1/14 times the density of air at the same temperature and pressure. The windage loss and noise are reduced in the machine as the revolving parts rotate in low-density hydrogen gas. Thus, the efficiency of the machine is increased.

Corona

When air is used as a cooling medium in generators, the corona discharge may take place to produce ozone, oxides of nitrogen, nitric acid, etc., which damages the insulation. If hydrogen cooling is used the corona effect does not take place and, as a result, the life of the insulation is increased.

LIMITATIONS OF HYDROGEN COOLING

- The frame of the hydrogen cooled alternator is more costly because of necessity to provide explosion proof construction and gas tight shaft seals.
- Means are necessary to admit hydrogen to the alternator without creating an explosion.
- Sourcing the air with CO_2 and then admitting hydrogen.
- By vacuum pumping the unit to 1/5 atmosphere and admitting hydrogen.
- Cooling coils carrying oil or water inside the casing are to be provided to extract heat from hydrogen.

5) DIRECT WATER COOLING IN SYNCHRONOUS GENERATOR

As hydrogen cooling is not sufficient to extract heat generated in large turbo alternators of sizes 500 MW or more. For such large machines, the volume of hydrogen gas required may be so large that its use may become uneconomical.

In such cases, the direct water cooling is used. In very large turbo-generators, rotors are direct hydrogen cooled and stator windings are direct demineralized water cooled. Water is circulated by an AC motor centrifugal pump. Cartridge filters are used to filter water. These filters are designed to prevent metallic corrosive particles generated in winding and piping from entering into winding hollow conductors.

Advantages of Water Cooling Over Hydrogen Cooling

- Water cooled system is faster and more efficient because the thermal conductivity of water is higher than that of hydrogen.
- The duct area of water is smaller to allow more space for conductors in the slot.

Disadvantages of Water Cooling

- The water, which is used for cooling should be highly purified so that the conductivity of water does not increase.
- Water cooling is more expensive than hydrogen cooling.

MODULE 5

Output Equation

Let

V_{ph} = phase voltage ;

I_{ph} = phase current

Z_{ph} = no of conductors/phase;

T_{ph} = no of turns/phase

N_s = Synchronous speed in rpm;

n_s = synchronous speed in rps

p = no of poles ;

ac = Specific electric loading

Φ= air gap flux/pole;

B_{av} = Average flux density

K_w = winding factor ;

D = Diameter of the stator;

L = Gross core length

C_o = Output coefficient;

Output of machine, $Q = 3 V_{ph} I_{ph} \times 10^{-3}$ kVA

Assuming induced emf, $E_{ph} = V_{ph}$

Output of machine, $Q = 3 E_{ph} I_{ph} \times 10^{-3}$ kVA

Induced emf, $E_{ph} = 4.44 f \phi T_{ph} K_w$

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

$$= 3 \times 4.44 \left(\frac{p n_s}{2}\right) \phi T_{ph} K_w I_z \times 10^{-3}$$

$f = \frac{p n_s}{2}$

$I_z = I_{ph}$

[As there is only one circuit per phase]

$$= 3 \times 2.22\, p n_s \phi\, T_{ph} k_w I_z \times 10^{-3}$$
$$= 1.11 \times 6\, p n_s \phi\, T_{ph} k_w I_z \times 10^{-3}$$
$$= 1.11 \times (6T_{ph})(p\phi) k_w n_s I_z \times 10^{-3}$$
$$= 1.11 \times Z (p\phi) k_w n_s I_z \times 10^{-3}$$
$$= 1.11\, k_w (p\phi)(I_z Z) n_s \times 10^{-3}$$
$$= 1.11\, k_w (\pi D L B_{av})(\pi D ac) n_s \times 10^{-3}$$
$$= (1.11\, \pi^2 B_{av} ac\, k_w \times 10^{-3}) D^2 L n_s$$
$$= (11\, B_{av} ac\, k_w \times 10^{-3}) D^2 L n_s$$
$$= C_0 D^2 L n_s$$

$$\boxed{Q = C_0 D^2 L n_s}$$

where C_0 - output coefficient

$$C_0 = 11\, B_{av} ac\, k_w \times 10^{-3}$$

Total no. of conductors

Z = no. of phases $\times 2T_{ph}$

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

$Z = 6T_{ph}$

Specific magnetic Loading

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

$p\phi = B_{av} \pi D L$

Specific electric Loading

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

$I_z Z = \pi D ac$

- D^2L- Active volume part of stator(m^3)
- The rating(output power) of motor is generally specified in HP.
- This HP is the power output at the shaft of motor
- kVA input, $Q = \frac{kW}{\eta \cos\Phi} = \frac{0.764 * HP}{\eta \cos\Phi}$
- η- Full load efficiency
- $\cos\Phi$- full load power factor

MAIN DIMENSIONS

- D-Armature diameter(stator bore)
- L- Stator core length

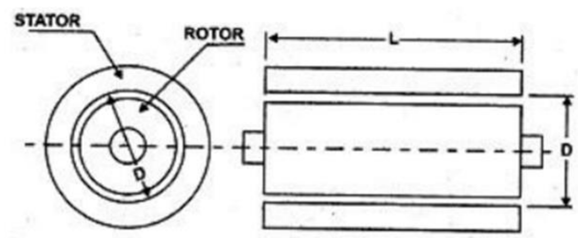


Fig. Main Dimensions D and L

OUTPUT EQUATION

Output Equation

$$Q = C_o * D^2L * n_s$$

$$\therefore D^2L = \frac{Q}{C_o * n_s}$$

$$\therefore D^2L \propto \frac{1}{C_o * n_s}$$

Size or volume of active part depends upon two factors:

- Output coefficient, C_0
- Speed, n_s
- For higher values of C_0 and n_s, D^2L decreases and hence the size of the machine decreases

Separation of D and L from D^2L depends on the ratio of **L/τ ratio of the motor**

Design Feature	Ratio L/τ
(1) Minimum cost	1.5 to 2
(2) Good Power Factor	1 to 1.25
(3) Good Efficiency	1.5
(4) Good Overall design	1

- Power factor plays a very important role in the performance of induction motors. Hence to obtain the best power factor the following relation will be usually assumed for separation of D and L.

$\boldsymbol{\tau = \sqrt{0.18L}}$

<u>ESTIMATION OF MAIN DIMENSIONS (D, L):</u>

We know

$$D^2L = \frac{Q}{C_0 n_s} \text{ ---------------------- (1)}$$

$$\left.\begin{cases} \dfrac{L}{\tau_p} = 1 & : \textit{Good Overall Design} \\ \quad = 1 \rightarrow 1.25 & : \textit{for Good PF} \\ \quad = 1.5 & : \textit{for higher } \eta \\ \quad = 1.5 \rightarrow 2.0 & : \textit{Overall Economical Design} \end{cases}\right\} \text{------- (2)}$$

Solving equation (1) & (2) we can find out D & L.

Peripheral Speed:

- The obtained values of D and L have to satisfy the condition imposed on the value of peripheral speed.
- For the normal design of induction motors the calculated diameter of the motor should be such that the peripheral speed must be below 30 m/s.
- In case of specially designed rotor the peripheral speed can be 60 m/s.

- $V_a = \pi D n_s$

SPECIFIC MAGNETIC LOADING(B_{av})

The average flux density over the air gap of a machine is known as specific magnetic loading

$$B_{av} = \frac{Total\ flux\ around\ the\ air\ gap}{Area\ of\ flux\ path\ at\ the\ air\ gap}$$

$$\boxed{B_{av} = \frac{P\emptyset}{\pi DL} = \frac{\emptyset}{\tau L} \quad where\ \tau = \frac{\pi D}{P}}$$

SPECIFIC ELECTRIC LOADING(ac)

- The number of stator ampere conductors per metre of stator periphery at the air gap is known as specific electric loading

$$ac = \frac{Total\ stator\ ampere\ conductors}{Stator\ periphery\ at\ air\ gap}$$

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

CHOICE OF SPECIFIC MAGNETIC LOADINGS

- **POWER FACTOR**: High flux density in air gap will draw large magnetizing current giving poor power factor. Hence the value of flux density in air gap should be small
- **IRON LOSS**: An increased value of gap density results in increased iron loss and decreased efficiency
- **OVERLOAD CAPACITY**: overload capacity increase with increase in flux density
- For 50 Hz machine the value of Bav lies between **0.3 – 0.6 Tesla.**
- For machines used in cranes, rolling mills etc., where large overload capacity is required, a value of **0.65 T** may be used.

CHOICE OF SPECIFIC ELECTRIC LOADING

- **Copper loss and temperature rise**: a large value of ac means that a greater amount of copper is employed in the machine. This gives higher copper losses and large temp. rise
- **Voltage**: a small value of ac should be taken for high voltage machines as in their case the space required for the insulation is large.
- **Overload capacity**: Higher value of ac, lower would be the overload capacity.

The value of ac depends upon the size of the motor, voltage of stator winding, type of ventilation and overload capacity desired. It varies between 5000 – 45000 ampere conductors per meter.

STATOR DESIGN

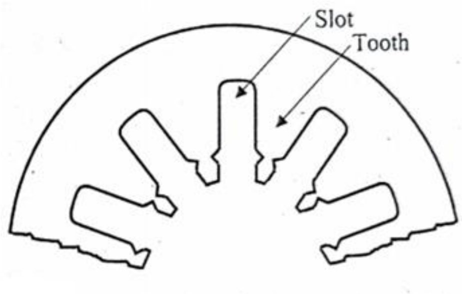
STATOR WINDING

- Double layer lap type winding with diamond shaped coils are generally used for stators
- Three phases of the winding can be connected in either star or delta depending upon starting methods employed

STATOR SLOTS

- In general two types of stator slots are employed in induction motors viz, open slots and semi-enclosed slots.
- Operating performance of the induction motors depends upon the shape of the slots

(i) **Open slots**: In this type of slots the slot opening will be equal to that of the width of the slots. In such type of slots, assembly and repair of winding are easy. However such slots will lead to higher air gap contraction factor and hence poor power factor.

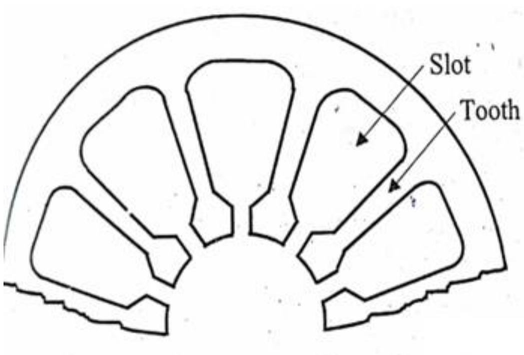


Open slots with parallel sided slots and tapered teeth

(ii) **Semi-enclosed slots**: In such type of slots, slot opening is much smaller than the width of the slot. Hence in this type of slots assembly of windings is more difficult and takes more time compared to open slots and hence it is costlier.

Semi-enclosed slots are usually preferred for IM because with their use the air gap contraction factor is small giving a small value of magnetizing current. The use of semi-enclosed slots results in low tooth pulsation loss .

In small motors where round conductors are used, the tapered slot with parallel sided tooth arrangement is used.



Semienclosed slots with tapered slots and paralled sided teeth

SELECTION OF NUMBER OF STATOR SLOTS:

- Number of stator slots must be properly selected at the design stage as such this number affects the weight, cost and operating characteristics of the motor.
- As there are no rules for selecting the number of stator slots, the advantages and disadvantages of selecting higher number slots help to serve as guidelines in the selection.

- Following are the advantages and disadvantages of selecting higher number of slots.

Advantages :

- (i) Reduced leakage reactance.
- (ii) Reduced tooth pulsation losses.
- (iii) Higher over load capacity.

Disadvantages:

- (i) Increased cost
- (ii) Increased weight
- (iii) Increased magnetizing current
- (iv) Increased iron losses
- (v) Poor cooling
- (vi) Increased temperature rise
- (vii) Reduction in efficiency

NUMBER OF STATOR SLOTS

- The number of slots/pole/phase should not be less than 2 otherwise the leakage reactance becomes high.
- The number of slots should be selected to give an integral number of slots per pole per phase.
- The stator slot pitch at the air gap surface should be between 15 to 25 mm.
- Stator slot pitch at the air gap surface, $\boldsymbol{y_{ss}}=\frac{\boldsymbol{\pi D}}{\boldsymbol{S_S}}$ where S_S is the number of stator slots
- Number of stator slots S_S = 3 pq
    - Where p -Number of poles
    - q- Number of stator slots/pole/phase >or = 2
- Total number of stator conductors Z_s = 6*T_{ph}
- Conductors/slot $Z_{ss} = \frac{Z_S}{S_S} = \frac{6*T_{ph}}{S_S}$
- *The number of conductors per slot must be an even integer for double layer winding*

SLOT LOADING

- Slot loading = $I_Z\ Z_{ss}$ and $I_Z = I_s$

TURNS PER PHASE

- Turns per phase can be calculated from emf equation of the alternator.
- Induced emf E_{ph}= 4.44 f Φ $T_{ph}K_w$ Hence turns per phase $\boldsymbol{T_{ph}} = \frac{\boldsymbol{E_{ph}}}{\boldsymbol{4.44\ f\ \Phi\ K_w}}$
- This equation is applicable when all the turns of a phase are connected in series.
    - E_{ph} = induced emf per phase
    - T_{ph} = no of turns/phase
    - K_w = winding factor may assumed as 0.955

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

AREA OF STATOR CONDUCTORS

- Area of each stator conductor $a_s = \frac{I_s}{\delta_s}$
- Stator current per phase $I_s = \frac{Input\ kVA * 1000}{3\text{Eph}}$
- 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

  Current density in stator δ_s- 3 to 5 A/mm^2

AREA OF STATOR SLOT

- Area of each slot=$\frac{Copper\ area\ per\ slot}{Space\ factor}$

  $=\frac{Z_{ss}a_s}{Space\ factor}$
- Space factor varies from 0.25 to 0.4

LENGTH OF THE MEAN TURN

- Length of the mean turn is calculated using formula
- Lmt = 2L + 2.3 τ + 0.24
- where L is the gross length of the stator and τ is pole pitch in meter.

STATOR TEETH

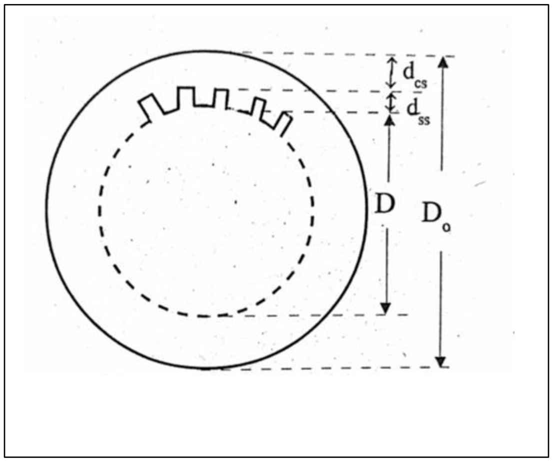
- Minimum tooth area per pole=$\frac{\Phi}{1.7}$
- Tooth area per pole= number of slots per pole x net iron length x width of tooth
- =(S_s/p) x L_i x W_{ts}
- Minimum width of stator tooth,

  $(W_{ts})\text{min} = \frac{\Phi}{1.7*(S_s/\text{p}) * L_i}$

STATOR CORE

- Flux in the stator core section $\Phi_c = \frac{\Phi}{2}$
- Area of stator core $A_c = \frac{\Phi}{2B_{cs}}$
- Area of stator core $A_c = L_i \times d_{cs}$
- $L_i \times d_{cs} = \frac{\Phi}{2B_{cs}}$
- Hence, depth of the core (d_{cs}) = $\frac{\Phi}{2B_{cs} * L_i}$
- Outer diameter of the stator core can be calculated as
- Do = D + 2(depth of stator slots + depth of core)

  = D + 2 d_{ss} + 2 d_{cs}



NOTE: 1. The stator is provided with radial ventilating ducts if the core length exceeds 100 to 125 mm.

2. The width of each duct is about 8 to 10 mm.

3. Input kVA $Q = \frac{kW}{\eta \cos\Phi}$

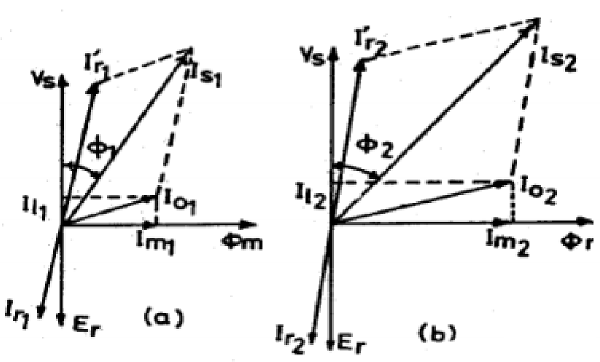
4. Input kVA $Q = \frac{hp \times 0.746}{\eta \cos\Phi}$

5. $K_{ws} = 0.955$

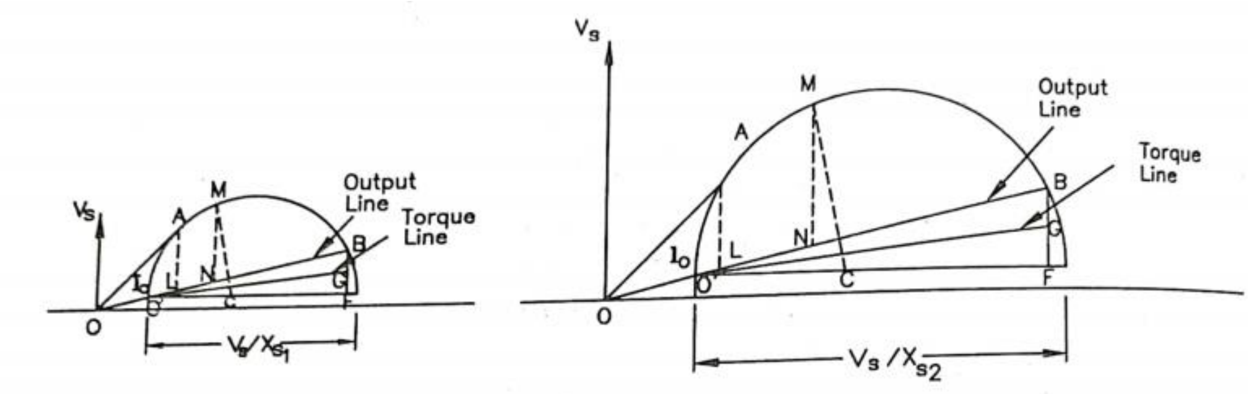
LENGTH OF AIR-GAP

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.

- **Power Factor**:- the mmf required to send the flux through air gap is proportional to the product of flux density and length of air gap. Fig. shows phasor diagrams of an induction motor with two different air gap lengths. With increase in air gap length, magnetizing mmf increases and hence greater the magnetizing current. Therefore, the phase angle between applied voltage and stator current will increase which gives low power factor.



- **Pulsation loss**:- the tooth pulsation losses, which is produced due to variation in reactance of the air gap, is reduced with large air gap.
- **Cooling**:- the large air gap provide better facilities for cooling at the gap surfaces due to the cylindrical surfaces of stator and rotor are separated by large distance.
- **Noise**:- noise in induction motor reduces with increase in air gap length due to reduction in leakage flux which is the cause of noise.
- **Overload Capacity**:- overload capacity of induction motor is the ratio of maximum output to rated output and the maximum output is obtained from circle diagram. The diameter of circle diagram is Vs /Xs where Xs is reactance of motor. The length of air gap affects the leakage reactance. If the length of air gap is large, the leakage flux is reduced, hence reduced value of leakage reactance. With decrease in the value of leakage reactance the diameter of circle diagram increases and hence the overload capacity increases.



- 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 tooth pulsation
- (v) Reduced noise

Disadvantages

- (i) Increased Magnetising current
- (ii) Reduced power factor

Magnetising 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.

Relations for Calculation of Length of Air Gap

(*i*) In order to estimate the length of air gap of small induction motors, the following expression can be used

$$l_g \doteq 0.2 + 2\sqrt{DL} \text{ mm}$$

where D and L are expressed in metre.

(*ii*) Another expression, which can be used for small machines, is

$$l_g = 0.125 + 0.35\,D + L + 0.015\,V_a \text{ mm}$$

where D and L are expressed in metre and V_a is the peripheral speed in metre per second.

(*iii*) The following relation may also be usefully used

$$l_g = 0.2 + D \text{ mm}$$

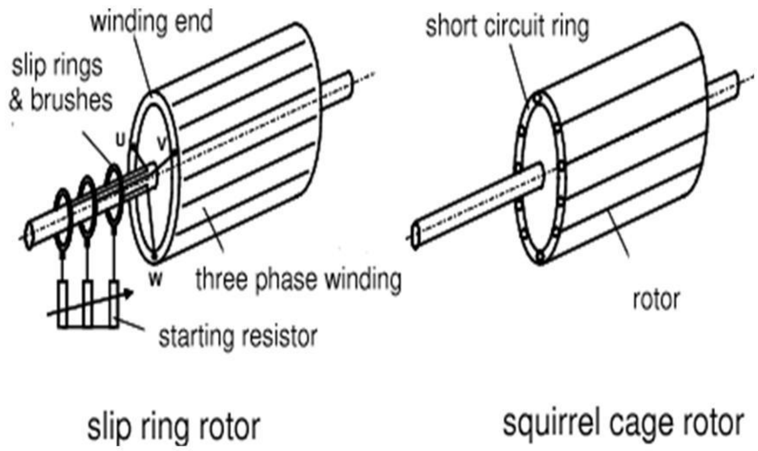
where D is expressed in metre.

(*iv*) For machines with journal bearings, following expression may be used

$$l_g = 1.6\sqrt{D} - 0.25 \text{ mm}$$

where D is expressed in metre.

Sr. No.	Wound or slip ring rotor	Squirrel cage rotor
1	Rotor consists of a three phase winding similar to the stator winding.	Rotor consists of bars which are shorted at the ends with the help of end rings.
2	Construction is complicated.	Construction is very simple.
3	Resistance can be added externally.	As permanently shorted, external resistance cannot be added.
4	Slip rings and brushes are present to add external resistance.	Slip rings and brushes are absent.
5	The construction is delicate and due to brushes, frequent maintenance is necessary.	The construction is robust and maintenance free.
6	The rotors are very costly.	Due to simple construction, the rotors are cheap.
7	Only 5% of induction motors in industry use slip ring rotor.	Very common and almost 95% induction motors use this type of rotor.
8	High starting torque can be obtained.	Moderate starting torque which cannot be controlled.
9	Rotor resistance starter can be used.	Rotor resistance starter cannot be used.
10	Rotor must be wound for the same number of poles as that of stator.	The rotor automatically adjusts itself for the same number of poles as that of stator.
11	Speed control by rotor resistance is possible.	Speed control by rotor resistance is not possible.
12	Rotor copper losses are high hence efficiency is less.	Rotor copper losses are less hence have higher efficiency.
13	Used for lifts, hoists, cranes, elevators, compressors etc.	Used for lathes, drilling machines, fans, blowers, water pumps, grinders, printing machines etc.



ROTOR DESIGN

1. DESIGN OF SQUIRREL CAGE ROTOR
2. DESIGN OF SLIP RING ROTOR(WOUND ROTOR)

DESIGN OF SQUIRREL CAGE ROTOR

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.
- With certain combinations of rotor and stator slots, the following problems may develop in the IM.
  - The motor may refuse to start.
  - The motor may crawl at some sub-synchronous speed.
  - Severe vibrations are developed and so the noise will be excessive.
- 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.

CRAWLING

- The rotating magnetic field produced in the air gap 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 motor with presence of 7th harmonics is to have a tendency to run the motor at one seventh of its normal speed.

COGGING

- In some cases where in the number of rotor slots are not proper in relation to number of stator slots the machine refuses to run and remains stationary.

- Under such conditions there will be a locking tendency between the rotor and stator. Such a phenomenon is called cogging.
- Rotor slots will be skewed by one slot pitch to minimize the tendency of cogging, torque defects like synchronous hooks and cusps and noisy operation while running.
- Effect of skewing will slightly increase the rotor resistance and increases the starting torque. However this will increase the leakage reactance and hence reduces the starting current and power factor.

NOTE:

1. CRAWLING

If the mechanical load on the shaft requires a constant load torque and if the torque developed by the rotor is below this load torque then the motor cannot accelerate upto its full speed but continues to run at a speed little lower than 1/7th synchronous speed. This condition of the motor is called crawling.

2. COGGING

When the number of rotor slots is equal to the number of stator slots, the speeds of all the harmonics produced by stator slotting coincide with the speed of corresponding rotor harmonics. Thus harmonics of every order would try to exert synchronous torques at their corresponding synchronous speeds and the machine would refuse to start. This is known as cogging.

RULES FOR SELECTING ROTOR SLOTS OF SQUIRREL CAGE MACHINES

The following general rules should be followed concerning the choice of rotor slots for squirrel cage machines.

(*i*) As stated earlier, the number of rotor slots should never be equal to stator slots but must either be large or smaller. Satisfactory results are obtained when the number of rotor slots is 15 to 30 per cent larger or smaller than the number of stator slots.

(*ii*) The difference between stator slots and rotor slots should not be equal to p, $2p$ or $5p$ to avoid synchronous cusps.

(*iii*) The difference between the number of stator and rotor slots should not be equal to $3p$ for 3 phase machines in order to avoid magnetic locking.

(*iv*) The difference between number of stator slots and rotor slots should not be equal to, 1.2, $(p \pm 1)$ or $(p \pm 2)$ to avoid noise and vibrations.

Summarizing,

$S_s - S_r$ should not be equal to

$$0, \pm p, \pm 2p, \pm 3p, \pm 5p$$
$$\pm 1, \pm 2, \pm (p \pm 1), \pm (p \pm 2).$$

The squirrel cage rotor consists of a laminated core, rotor bars and end-rings. The rotor bars and end rings are made of aluminium or copper. The length of the rotor is same as that of stator. Some manufacturers, keep the length of rotor slightly higher than that of stator, in order to utilize the end fluxes. The diameter of the rotor is slightly lesser than the stator to avoid mechanical friction between the stationary stator and rotating rotor.

The diameter of rotor, $D_r = D - 2l_g$

where, D = Diameter of stator bore

l_g = Length of air gap

Length of bar, $L_b = L + 0.045$ m

Rotor bar current, $I_b = \frac{6 I_s T_s}{S_r} K_{ws} \cos\phi$

$$\approx 0.85 \frac{6 I_s T_s}{S_r}$$

where, I_s = Stator current per phase

T_s = Stator turns per phase

S_r = Number of rotor slots

ALTERNATE METHOD

- Rotor Bar Current: Bar current in the rotor of a squirrel cage induction motor may be determined by comparing the mmf developed in rotor and stator.
- The stator mmf is about 15% higher because of the magnetizing mmf.
- Rotor mmf = 0.85 (stator mmf)
- Number of rotor bars = N_b = S_r= number of rotor slots
- Rotor mmf = $\frac{I_b S_r}{2}$
- Stator mmf = $3.I_s.T_s$
- Thus $\frac{I_b S_r}{2} = 0.85\ (3.I_s.T_s)$
- Rotor bar current ,I_b =$0.85\frac{(6.I_s.T_s)}{S_r}$

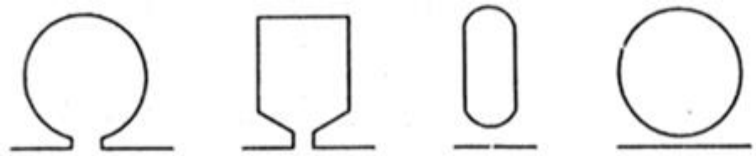
AREA OF ROTOR BAR

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

The current density in the rotor bar, δ_b may be taken between 4 to7A/mm^2.

SHAPE OF ROTOR SLOTS

- The rotor slots for squirrel cage rotor may be either closed or semi-enclosed types.



Types of rotor slots.

Advantages of closed slots

- Low reluctance
- Less magnetizing current
- Quieter operation
- Large leakage reactance and so starting current is limited

Disadvantage of closed slots

- Reduced over load capacity

The semi closed slots provides better overload capacity.

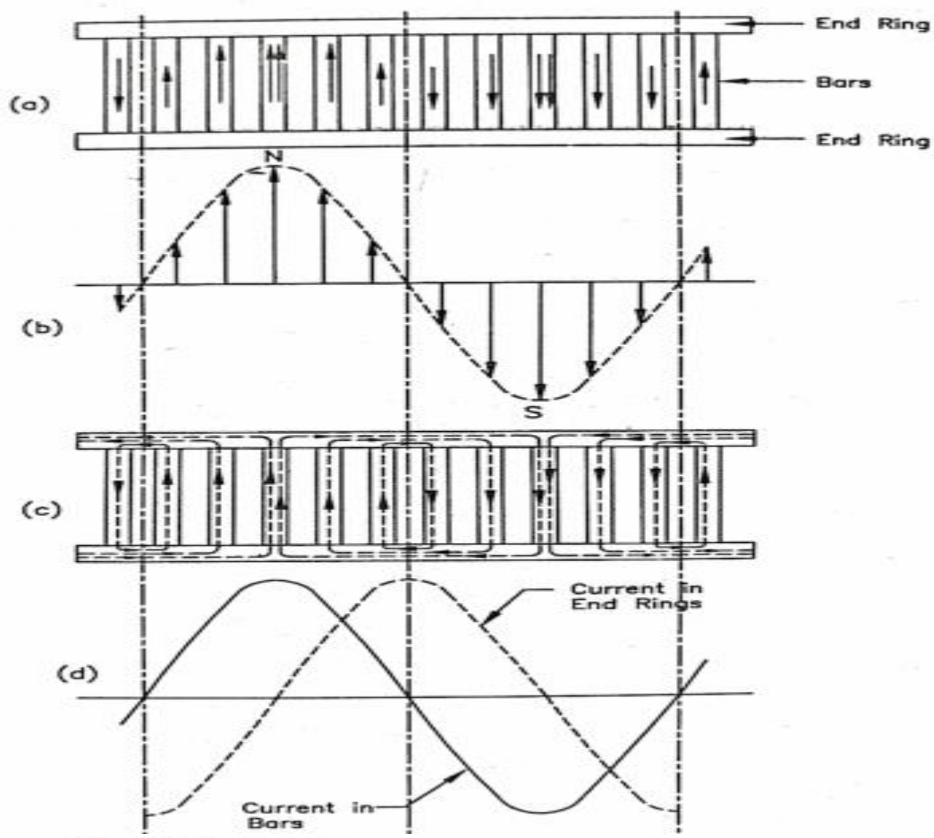
Generally, the rotor slots and so the rotor bars are rectangular in shape. In rectangular bars, during starting most of current flows through top portion of the bar and so the effective rotor resistance is increased. This improves the starting torque.

ROTOR SLOT INSULATION

- No insulation is used between bars and rotor core.
- A clearance of 0.15 to 0.4 mm can be left between rotor bars and the core depending upon whether slots are skewed or not.
- Higher clearances have to be left for the skewed slots

DESIGN OF END RING

- End Ring Current: All the rotor bars are short circuited by connecting them to the end rings at both the end rings. As the rotor is a short circuited, there will be current flow because of induced emf in the rotor bars.
- 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.



The distribution of current in the bars and end rings of a squirrel cage motor is complicated. It can be shown that if flux distribution is sinusoidal then the bar current and end ring current will also be sinusoidal.

$$\left.\begin{array}{l}\text{Maximum value of}\\ \text{end ring current}\end{array}\right\} I_{e(max)} = \frac{\text{Bars per pole}}{2} \times \text{Current per bar}$$

$$= \frac{S_r}{2p} I_{b(max)}$$

However, current is not maximum in all the bars under one pole at the same time but varies according to sine law, hence the maximum value of the current in the end ring is the average of the current of half the bars under one pole.

$$\left.\begin{array}{l}\therefore \text{Maximum value of}\\ \text{end ring current}\end{array}\right\} I_{e(max)} = \frac{\text{Bars per pole}}{2} \times I_{b(ave)} = \frac{S_r / p}{2} \times \frac{2}{\pi}\ I_{b(max)}$$

$$= \frac{S_r / p}{2} \times \frac{2}{\pi} \times \sqrt{2}\ I_b = \frac{\sqrt{2}\ S_r I_b}{\pi p}$$

(Here the bar current is sinusoidal. $\therefore I_{b(ave)} = \frac{2}{\pi} I_{b\,(max)}$ and $I_{b(max)} = \sqrt{2}\ I_b$

where I_b *= rms value of bar current).*

The end ring current also varies sinusoidally,

$$\left.\begin{array}{l}\therefore \text{rms value of end}\\ \text{ring current}\end{array}\right\} I_e = \frac{1}{\sqrt{2}}\ I_{e(max)} = \frac{1}{\sqrt{2}} \times \frac{\sqrt{2}\ S_r\ I_b}{\pi\ p} = \frac{S_r I_b}{\pi p}$$

AREA OF END RING

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

Let current density in the end ring δ_e be 4 to 7 A/mm²

Also, Area of end ring, a_e = Depth of end ring × Thickness of end ring.

$= d_e \times t_e$

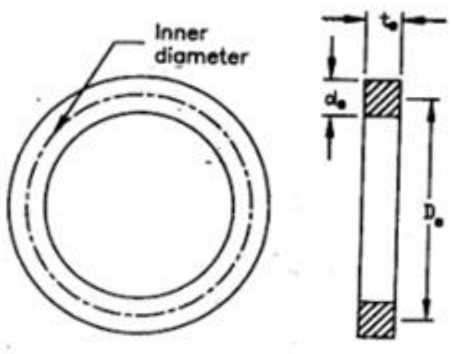


Fig. Dimensions of end ring.

- $\frac{Rotor\ Cu\ loss}{Rotor\ output} = \frac{s}{1-s}$
- Speed of rotor ,n_r=(1-s) n_s
- I^2R loss(Cu loss) = $S_r I_b^2 \ \ r_b$
- $r_b = \frac{\rho L_b}{a_b}$

DESIGN OF SLIP RING ROTOR (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.

ROTOR WINDING

For small motors mush windings are employed for the rotor. It is usual to use several wires in parallel per turn, to keep the conductor small enough to go through the narrow slot opening.

For large motors, a double layer bar type wave winding is used. The winding has generally two bars per slot. The bars are pushed through partially closed slots and are bent to shape at the other end.

In motors of output more than 750 kW, we have to use more number of bars per slot to reduce the current handled by slip rings. This type of winding is called barrel winding and is usually wave wound.

NUMBER OF ROTOR TURNS

The rotor is equivalent to secondary of a transformer and the voltage between slip rings is maximum when the rotor is at rest. The rotor voltage on open circuit between slip rings should not exceed 500 volt for small machines where hand operated starters and switchgear are employed. For large size machines the voltage between slip rings can be upto 2000 Volt.

Let T_s, T_r = number of turns per phase for stator and rotor respectively,

K_{ws}, K_{wr} = winding factor for stator and rotor respectively,

E_s = stator voltage per phase,

E_r = rotor voltage per phase at standstill.

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

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

E_r should not exceed 500 V and 500/√3 = 290 V for delta and star connected machines respectively.

ROTOR CURRENT

The rotor amper-turn is assumed as 85% of stator ampere-turn.

$$\therefore \text{Rotor ampere-turn} = 0.85 \times \text{stator ampere-turn}$$

$$I_r T_r = 0.85\, I_s\, T_s$$

Hence, rotor current, $I_r = 0.85\, \frac{I_s T_s}{T_r}$

AREA OF ROTOR CONDUCTORS

The current density for rotor conductors is assumed same as that of stator conductors. The range of current density in rotor is 3 to 5 A/mm²

Let, δ_r = Current density in rotor

$$\therefore \text{Area of rotor conductor, } a_r = \frac{I_r}{\delta_r}$$

NUMBER OF ROTOR SLOTS

The discussions made on choice of squirrel cage rotor slots are also applicable to the choice of wound rotor slots. For wound rotors the windings are always three phase winding and they are star connected at one end and the other three end are terminated on three slip rings mounted on the shaft.

Since the windings are three phase windings, the number of slots should be such that a balanced winding is obtained. Generally windings with an integral number of slots per pole per phase are used for the rotor. When fractional slot windings are used, it is preferable to have the number of slots as multiples of phases and pair of poles.

ROTOR TEETH

The width of rotor slot should be such that the flux density in the rotor teeth does not exceed about 1.7 Wb/m². The maximum flux density for rotor teeth occurs at their root as their section is minimum there.

$$\text{Minimum width of rotor teeth } W_{ir} \text{ (min.)} = \frac{\Phi_m}{1.7 \times (S_r / p) \times L_i}$$

It should be checked that the value of minimum tooth width actually provided in the machine is higher than the value given by Eqn. 10.20.

Minimum width of tooth actually provided

$$W_{ir} = \text{rotor slot pitch at the root} - \text{rotor slot width} = \frac{\pi(D_r - 2d_{sr})}{S_r} - W_{sr}$$

where d_{sr} = depth of rotor slot and W_{sr} = width of rotor slot.

ROTOR CORE

The flux density in the rotor core is generally equal to stator core density.

$$\text{Depth of rotor core} \quad d_{cr} = \frac{\Phi_m}{2 \times B_{cr} \times L_i}$$

where B_{cr} = flux density in the rotor core.

Inside diameter of rotor lamination $D_i = D_r - 2(d_{sr} + d_{cr})$

The flux density in rotor teeth and core can be taken slightly higher than those in the stator teeth and core. This is because the iron losses in the rotor are very small owing to small value of frequency of rotor currents.

where, d_{sr} = Depth of rotor slot

DISPERSION COEFFICIENT

- Power factor is an important factor in designing of induction motor.
- Power factor depends upon two factors:
- i) Magnetizing current :a large value of the magnetizing current indicates poor power factor
- ii) Ideal short circuit current (Isc): it is defined as the current drawn by the motor at standstill neglecting its resistance. A large value of ideal short circuit current will be drawn for small value of leakage reactance giving good power factor.
- Dispersion coefficient defined as the ratio of magnetizing current to ideal short circuit current.
- Thus dispersion coefficient,
- $\sigma = \frac{I_m}{I_{sci}} = \frac{I_m}{E_s/X_s}$ =Im.Xs /Es
- Where, Isci = Es /Xs

NOTE:

1. DISPERSION COEFFICIENT

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

Dispersion coefficient, $\sigma = I_m / I_{sci}$

where, I_m = Magnetizing current

I_{sci} = E_s/X_s = Ideal short circuit current

E_s = Stator phase voltage

X_s = Total leakage reactance of the motor referred to stator

Higher value of dispersion coefficient results in

- Poor power factor
- Reduced over-load capacity
- Reduced output

2. FULL LOAD SLIP

The value of slip at full load is determined by the rotor resistance. A reasonable value of rotor resistance to be incorporated in the rotor can be obtained by the knowledge of reasonable values of full load slip. The value of slip, *s*, is derived from the following relationship

$$\frac{\text{rotor copper loss}}{\text{rotor output}} = \frac{s}{1-s}$$

where *s* is the per unit slip.

3. Coil Span = $\frac{\text{Rotor slots}}{\text{Number of poles}}$

PROBLEMS

PROBLEM 1 *Find the main dimensions of a 15 kW, 3 phase, 400 V, 50 Hz, 2810 r.p.m. squirrel cage induction motor having an efficiency of 0.88 and a full load power factor of 0.9. Assume :*

specific magnetic loading = 0.5 Wb/m^2 ; specific electric loading = 25000 A/m.

Take the rotor peripheral speed as approximately 20 m/s at synchronous speed.

Solution.

kVA input $$Q = \frac{15}{0.88 \times 0.9} = 18.94.$$

Output co-efficient $$C_0 = 11\,K_w\,B_{av}\,ac \times 10^{-3}$$
$$= 11 \times 0.955 \times 0.5 \times 25000 \times 10^{-3} = 131.3$$

The speed of the rotor at full load is 2810 r.p.m. and the nearest synchronous speed corresponding to 50 Hz is 3000 r.p.m.

Synchronous speed $n_s = 3000/60 = 50$ r.p.s.

$\therefore$ Product $$D^2L = \frac{Q}{C_0 n_s} = \frac{18.94}{131.3 \times 50} = 2.88 \times 10^{-3}\ \text{m}^3.$$

The rotor diameter in an induction motor is almost equal to stator bore.

$\therefore$ $$\pi D n_s = 20$$

or $$D = \frac{20}{\pi \times 50} = 0.1257\ \text{m},$$

and $$L = \frac{2.88 \times 10^{-3}}{(0.1275)^2} = 0.177\ \text{m}.$$

EXAMPLE: 01

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

Given Data

11 kW	delta connected	1425 rpm
3ϕ	double layer winding	$B_{av} = 0.45$ Wb/m^2
4 - pole	**ac** = 23000 amp.cond./m.	pf = 0.88
400 V	$\eta = 0.85$	$L/\tau = 1$

Solution

$$\text{kVA input} = \frac{\text{Output}}{\eta \times \text{pf}} = \frac{11}{0.85 \times 0.88} = 14.7\ \text{kVA}$$

$$\text{Synchronous speed, } n_s = \frac{2f}{p} = \frac{2 \times 50}{4} = 25\ \text{rps}$$

Let, $K_{ws} = 0.955$

$$C_0 = 11\, K_{ws} B_{av}\, ac \times 10^{-3}$$
$$= 11 \times 0.955 \times 0.45 \times 23000 \times 10^{-3} = 108.7268\ \text{kVA}/\text{m}^3\text{-rps}$$

$$\text{kVA input,} \quad Q = C_0\, D^2\, L\, n_s$$
$$\therefore D^2 L = \frac{Q}{C_0 n_s} = \frac{14.7}{108.7268 \times 25} = 0.0054\ \text{m}^3$$

Given that, $L/\tau = 1 \quad \therefore L = \tau = \frac{\pi D}{p}$

Put, $L = \frac{\pi D}{p}$ in the equation for D^2L

$$\therefore D^2L = D^2\frac{(\pi D)}{p} = 0.0054 \quad \text{or} \quad D^3\frac{\pi}{p} = 0.0054$$

$$\therefore D = \left(\frac{0.0054 \times p}{\pi}\right)^{1/3} = 0.1902 \text{ m}$$

$$L = \frac{\pi D}{p} = \frac{\pi \times 0.1902}{4} = 0.1494 \text{ m.}$$

$$\boxed{\mathbf{D = 0.19\ m} \quad \text{and} \quad \mathbf{L = 0.15\ m}}$$

$$\text{Maximum flux per pole}, \phi_m = \frac{B_{av}\pi DL}{p} = \frac{0.45 \times \pi \times 0.19 \times 0.15}{4} = 0.01 \text{ Wb}$$

Since the stator is delta connected, the line voltage is same as phase voltage.

$$\text{Stator turns per phase, } T_s = \frac{E_s}{4.44\, f\phi_m K_{ws}}$$

$$= \frac{400}{4.44 \times 50 \times 0.01 \times 0.955} = 188$$

The stator slots should be multiple of q, where q is slots per pole per phase.

Stator slots, S_s = Number of phaes × Poles × q

For $q = 2,\ S_s = 3 \times 4 \times 2 = 24$

For $q = 3,\ S_s = 3 \times 4 \times 3 = 36$

For $q = 4,\ S_s = 3 \times 4 \times 4 = 48$

The stator slot pitch should lie between 15 mm to 25 mm.

When, $S_s = 36,\ y_{ss} = \frac{\pi D}{S_s} = \frac{\pi \times 0.19 \times 10^3}{36} = 16.58$ mm

When $S_s = 36$, the slot pitch (y_{ss}) lies between 15 to 25 mm. Hence the stator slots can be 36.

Conductors per slot, $Z_{ss} = \frac{6T_s}{S_s} = \frac{6 \times 188}{36} = 31.333$

Z_{ss} should be even integer for double layer winding and so it is 30 or 32.

Let, $Z_{ss} = 32$, Total stator conductors $= S_s \times Z_{ss} = 36 \times 32 = 1152$

New value of turns per phase, $T_s = \frac{Z_{ss}S_s}{6} = \frac{32 \times 36}{6} = 192$

Results

Diameter of stator	=	0.19 m
Length of stator	=	0.15 m
Number of stator slots	=	36
Total stator conductor	=	1152
Turns per phase	=	192

EXAMPLE 3

Estimate the stator core dimensions, number of stator slots and number of stator conductors per slot for a 100 kW, 3300V, 50Hz, 12 pole, star connected slip ring induction motor. $B_{av} = 0.4$ Wb/m², **ac** = 25000 amp.cond./m, $\eta = 0.9$, pf = 0.9. Choose main dimensions to give best power factor. The slot loading should not exceed 500 amp. conductors.

Given Data

100 kW	3300 V	$B_{av} = 0.4$ Wb/m²
50 Hz	12 pole	**ac** = 25000 amp.cond./m.
$\eta = 0.9$	pf = 0.9	slot loading ≤ 500 amp.cond.
star connected	3 phase	

Solution

$$\text{kVA input, } Q = \frac{\text{output}}{\eta \times \text{pf}} = \frac{100}{0.9 \times 0.9} = 123.457 \text{ kVA}$$

Let, $K_{ws} = 0.96$

$$\text{Output coefficient, } C_0 = 11\ B_{av}\ \mathbf{ac}\ K_{ws} \times 10^{-3}$$
$$= 11 \times 0.4 \times 25000 \times 0.96 \times 10^{-3}$$
$$= 105.6 \text{ kVA/m}^3\text{-rps}$$

$$\text{Synchronous speed, } n_s = \frac{2f}{p} = \frac{2 \times 50}{12} = 8.33 \text{ rps}$$

We know that, kVA input, $Q = C_o D^2 L n_s$

$$\therefore D^2L = \frac{Q}{C_o n_s} = \frac{123.457}{105.6 \times 8.33} = 0.1403 \text{ m}^3$$

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

$$\text{But, } \tau = \frac{\pi D}{p}, \qquad \therefore \frac{\pi D}{p} = \sqrt{0.18\ L}$$

$$\text{On squaring we get, } \frac{\pi^2 D^2}{p^2} = 0.18L$$

$$\therefore D^2 = \frac{0.18 \times p^2}{\pi^2} L = \frac{0.18 \times 12^2}{\pi^2} L = 2.6262\ L$$

Put, $D^2 = 2.6262\ L$ in the equation for $D^2\ L$

$$\therefore D^2\ L = 2.6262\ L \times L = 0.1403$$

$$L = \sqrt{\frac{0.1403}{2.6262}} = 0.2311 \text{ m} \approx 0.23 \text{ m}$$

$$D^2 = 2.6262\ L, \qquad \therefore D = \sqrt{2.6262 \times 0.23} = 0.7772 \text{ m} \approx 0.78 \text{ m}$$

L = 0.23 m and **D = 0.78 m**

Since the stator is star connected,

$$\text{Stator voltage per phase, } E_s = \frac{3300}{\sqrt{3}} = 1905.256 \text{ V}$$

$$\text{Flux per pole, } \phi_m = \frac{B_{av} \pi D L}{p} = \frac{0.4 \times \pi \times 0.78 \times 0.23}{12} = 0.0188 \text{ Wb}$$

$$\text{Stator turns per phase, } T_s = \frac{E_s}{4.44 \, f \, \phi_m K_{ws}} = \frac{1905.256}{4.44 \times 50 \times 0.0188 \times 0.96} = 478$$

The stator slot pitch should lie between 15 to 25 mm.

$$\text{Stator slots, } S_s = \frac{\pi D}{y_{ss}}$$

$$\text{When } y_{ss} = 15\text{mm}, \; S_s = \frac{\pi \times 0.78}{15 \times 10^{-3}} = 163$$

$$\text{When } y_{ss} = 25\text{mm}, \; S_s = \frac{\pi \times 0.78}{25 \times 10^{-3}} = 98$$

The stator slots, S_s should lie between 98 to 163.

The stator slots be multiple of q, where q is slot per pole per phase.

Stator slots, S_s = Number of phases × poles × q

When, $q = 2$, $S_s = 3 \times 12 \times 2 = 72$

When, $q = 3$, $S_s = 3 \times 12 \times 3 = 108$

When, $q = 4$, $S_s = 3 \times 12 \times 4 = 144$

When, $q = 5$, $S_s = 3 \times 12 \times 5 = 180$

The S_s values of 108 and 144 lie in the range of 98 to 163.

$\therefore$ S_s can be either 108 or 144.

Check for slot loading

$$\text{Stator current per phase} = \frac{\text{kVA} \times 10^3}{\sqrt{3} \times V_L} = \frac{123.457 \times 10^3}{\sqrt{3} \times 3300} = 21.6 \text{ A}$$

(since star connected, $I_L = I_{ph}$)

When $S_s = 108$

$$Z_{ss} = \frac{6T_s}{S_s} = \frac{6 \times 478}{108} = 26.55 \approx 26$$

$$\text{Slot loading} = Z_{ss}I_s = 26 \times 21.6$$
$$= 561.6 \text{ amp.cond.}$$

When $S_s = 144$,

$$Z_{ss} = \frac{6T_s}{S_s} = \frac{6 \times 478}{144} = 19.91 \approx 20$$

$$\text{Slot loading} = Z_{ss}I_s = 20 \times 21.6$$
$$= 432 \text{ amp.cond.}$$

When $S_s = 144$, the slot loading does not exceeds 500 amp.cond. Hence 144 slots is suitable for the machine.

$$\text{Total stator conductors} = S_s \times Z_{ss} = 144 \times 20 = 2880$$

$$\text{New value of turns per phase, } T_s = \frac{Z_{ss}\, S_s}{6} = \frac{20 \times 144}{6} = 480$$

Result

Diameter of stator	=	0.78 m
Length of stator	=	0.23 m
Number of stator slots	=	144
Total stator conductors	=	2880
Turns per phase	=	480

COMPUTER AIDED DESIGN (CAD)

Introduction to CAD

CAD is the use of computer software to design and document a product's design process. Engineering drawings uses graphical symbols such as points, lines, curves, planes and shapes. Essentially, it gives detailed description about any component in a graphical form. Engineering drawing has been in use for more than 2000 years. However, the use of orthographic projections was formally introduced by the French mathematician Gaspard Monge in the eighteenth century.

Since visual objects become more important than languages, engineering drawings have evolved and become popular over the years. While earlier engineering drawings were handmade, studies have shown that engineering designs were quite complicated. A solution to many engineering problems requires a combination of organization, analysis, problem solving principles and a graphical representation of the problem. Objects in engineering are represented by a technical drawing (also called as drafting) that represents designs and specifications of the physical object and data relationships. Since a technical drawing is precise and communicates all information of the object clearly, it has to be precise. There comes the importance of CAD.

CAD stands for Computer Aided Design. CAD is used to design, develop and optimize products. It is very versatile. CAD is extensively used in the design of tools and equipment required in the manufacturing process as well as in the construction domain. CAD enables design engineers to layout and to develop their work on a computer screen, print and save it for future editing.

Uses of CAD

CAD is used to accomplish preliminary design and layouts, design details and calculations, creating 3 – D models, creating and releasing drawings as well as interfacing with analysis, marketing, manufacturing and end – user personnel.

CAD facilitates the manufacturing process by transferring detailed information about a product in an automated form that can be universally interpreted by trained personnel. It can be used to produce either two dimensional or three-dimensional diagrams. The use of CAD software tool allows the object to be viewed from any angle, even from the inside looking out. One of the main advantages of a CAD drawing is that the editing is a fast process as compared to manual method.

Apart from detailed engineering of 2D or 3D models, CAD is widely used from conceptual design and layout of products to definition of manufacturing of components. CAD reduces design time by allowing precise simulation rather than builds and test physical prototypes. Integrating CAD with CAM (Computer Aided Manufacturing) streamlines the product development even more. CAD is currently widely used for industrial products, animated movies and other applications. A special printer or plotter is usually required for printing professional design renderings. CAD programs uses either vector-based graphics or raster graphics that show how an object will look.

Types of CAD Software

1. **Two-dimensional CAD (2D CAD):** 2D CAD is the pioneer of CAD software and was developed in the early 70's. At that time, major automobile, aerospace and other engineering companies developed in – house tools to automate repetitive drafting requirements. 2D CAD relies on basic geometric shapes like lines, rectangles, circles etc. to produce flat drawings. These types of software have been first developed way back in 1970's. Auto Desk is one of the pioneering companies that have played a significant role in developing CAD software.
2. **Three-dimensional CAD (3D CAD):** 3D CAD is a step up from the older 2D CAD software. As the processing power of computers increased and the graphic display capabilities improved, 3D CAD has become an increasingly popular design tool. 3D CAD allows the creation of 3D images that are realistic. These images are called 3D models as they can be viewed and rotated in any direction – X, Y or Z. We will also get isometric and perspective views from any angle using 3D CAD. 3D CAD tools were introduced in 1980's by a partnership between IBM-Dassults. 3D CAD quickly became popular because of enhanced visual capability. The rapid advancement of 3D software today has helped quick turnaround in product design, giving birth to the concept for product life cycle management. A few of today's leading 3D CAD software includes Solid Edge, Solid Works and Uni-graphics NX.

   3D CAD can be further classified as:

   i) **Wire-frame Models:** They creates skeleton like models with lines and arcs. Since they appear to be made of wires and everything in the background is visible, they are called wire-frame models. They are not very popular anymore.

ii) **Surface Models:** Unlike wire frames, these models are created by joining 3D surfaces. Since nothing in the background is visible, the surface models are quite realistic.

iii) **Solid Models:** They are considered to be the most useful CAD models. Although they appear to be the same as surface models, they also have additional properties like weight, volume and density just like actual physical objects. These models are commonly used as prototypes to study engineering designs.

Analysis, Synthesis and Hybrid Methods of CAD

- **Analysis Method**

In this method, the computer is used only for the purpose of analysis and all the decisions are taken manually by the designer. In analysis method, the choice of basic parameters and types of construction are done by the designer. These are given as inputs to the computer for estimation of different machine dimensions and performance calculation. The performance calculated by computer is then critically examined by the designer according to the specifications to be achieved by the machine.

If the design is satisfactory, the output given is the final design detail. If it is not satisfactory, the designer can make other suitable choice of the parameters to recalculate the performance. This process can be repeated till the performance calculated above is satisfactory. Considerable time is saved by calculating the performance with the help of computer inspired by human calculations. The analysis method can be initially applicable in design of electrical machines. The flow chart for analysis method is given in fig. 1.

The program for analysis method is simple, easy to understand and use. It saves much calculation time and can be referred or used in larger and sophisticated design programs. The analysis method gives widely acceptable results. The advantage of this method is that the logical decisions are taken by the designers and hence simple programs can be used.

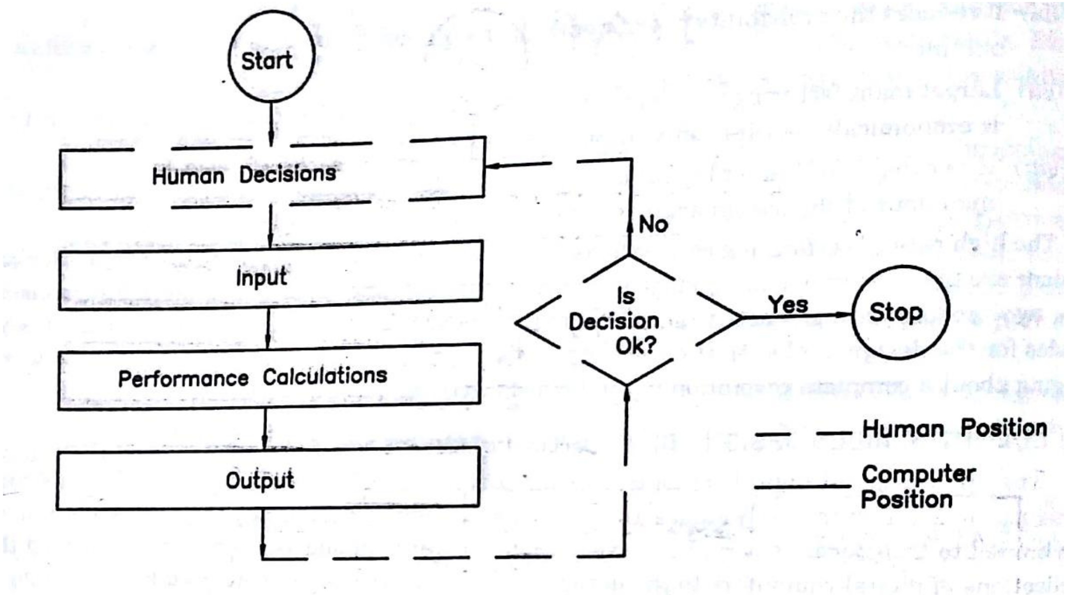
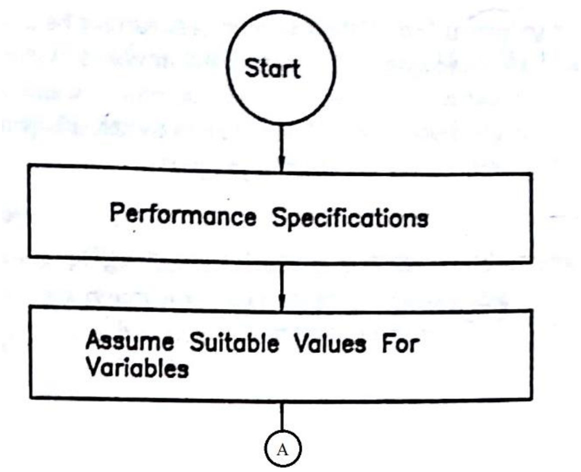


Fig. 1 Flow chart of analysis Method

- **<u>Synthesis Method</u>**

In analysis method, the logical decisions are taken by the designers, i.e, when the output is not matching with the desired specifications then designers selects the suitable parameters and again the performance analysis is done.

In synthesis method, the logical decisions are taken by the computers. The logical decisions include the suitable change in parameters to achieve the desired design and performance. The logical decisions are considered as a set of instructions in the program. The flow chart for synthesis method is shown in fig. 2. In synthesis method, the analysis and decision both are done by the computers. So, the time required in this method is very less.



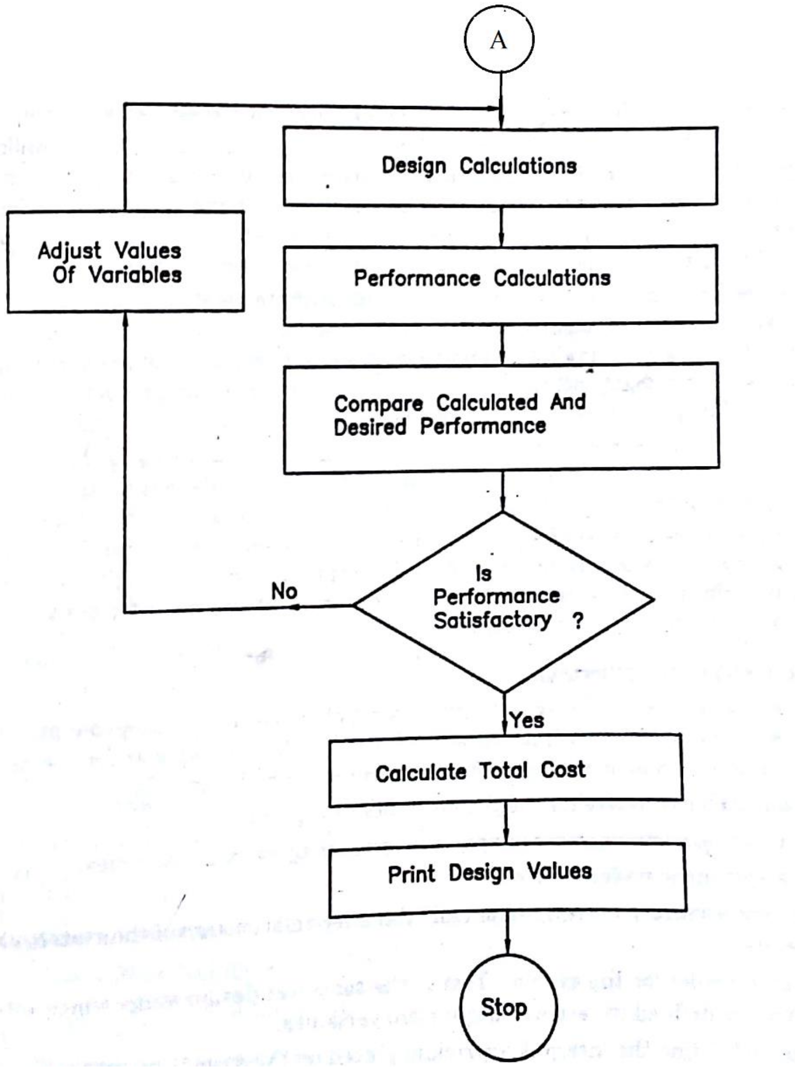


Fig. 2 Flow chart of synthesis method

In synthesis method, the following problems may be encountered:

- ✓ The materials (conducting/ magnetic/ insulating), manufacturing techniques, specifications etc. are always changing and these changes must be incorporated in the program.
- ✓ When a machine is to be designed, there are many parameters to be considered in design procedure and hence to get an optimized design, there may be so many combinations of parameters which can cause different logic decisions and bulky programs.

- **Hybrid Method**

When both analysis and synthesis methods are used simultaneously to design a machine, then this is called hybrid method. The logical decisions require large no. of instructions. These instructions should be considered in the programs. The program which is made for design should have proper set of instructions to take the logical decisions. It is important that the program used for synthesis method should be prepared on the basis of good technical knowledge, experience and collective decisions of design engineers. These may involve huge investments and sometimes complicated. So, to make the design procedure easier, the logical decisions can be partly taken by the designers and partly by the computers. By using both the methods together means that the computational work can largely be done by computer programs and some design decisions may be taken by designers which will reduce the complication of design programs. Thus, both analysis and synthesis methods can be involved.

Introduction to Finite Element Analysis

The Finite Element Analysis (FEA), also known as Finite Element Method (FEM), is a numerical technique to obtain an approximate solution to a class of problems governed by elliptic partial differential equations. Such problems are called as boundary value problems as they consist of a partial differential equation and the boundary conditions.

The finite element method converts the elliptic partial differential equation into a set of algebraic equations which are easy to solve. The initial value problem which consists of a parabolic or hyperbolic differential equation contains time as one of the independent variables. To convert the time or temporal derivatives into algebraic expressions, another numerical technique like the Finite Difference Method (FDM) is required. Thus, to solve an initial value problem one need FEA as well as FDM where the spatial derivatives are converted to algebraic expressions by FEM and the temporal derivatives are converted into algebraic equations by FDM.

The FEM formulation of the problem results in a system of algebraic equations. The method yields approximate values of the unknowns at discrete no. of points over the domain. To solve a problem, it subdivides the large problem into smaller simpler parts that are known as ‘finite elements’. The simple equations that model the finite elements are then assembled into a system of equations that models the entire problem.

Historical Background of FEA

The search for methods to discretize continuum mechanics problems has historically been tackled with different approaches by engineers and mathematicians (fig. 3).

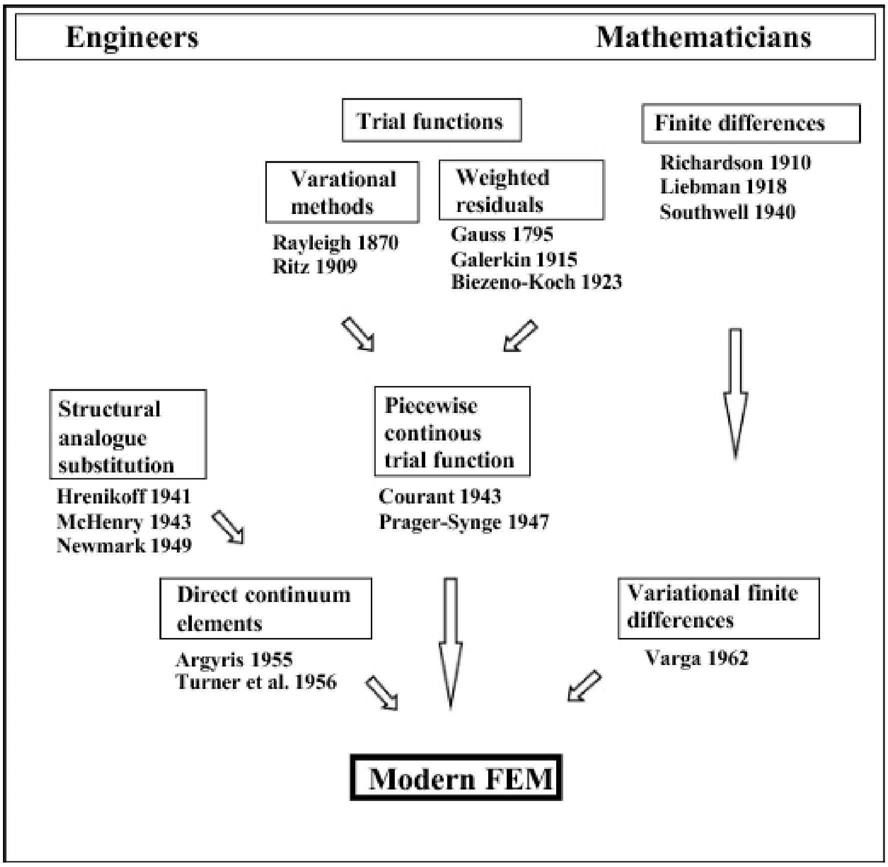


Fig. 3 Historical background of modern finite element method

An analysis of complex structures and other systems in a matrix formulation is now unthinkable without the finite element method. Our personal brief is that the origins of such a rich and applicable method cannot be attributed solely to one person or school of thought but rather to a synergy of various scientific developments at various research establishments. The notion of geometrical division can be traced back to the Greek natural philosopher Archimedes who in order to compute the area of a complex shape divided it into triangles and quadrilaterals whose area could be easily computed, the assembly of the individual areas provided the total area of the complex shape.

More recently, Courant used variational and minimization arguments for the solution of physical problems. Courant, Prager and Synge had proposed the concept of regional discretization which is essentially equivalent to the assumption of constant strain fields within the elements.

The adaptation however and the development of these concepts for structural analysis and other physical and technical problems was not conceptually achieved until during and shortly after World War II.

Advantages of FEM

1. Modelling of complex geometries and irregular shapes are easier as varieties of finite elements are available for discretization of domain
2. Boundary conditions can be easily incorporated in FEM
3. Different types of material properties can be easily accommodated in modelling from element to element or even within an element
4. Higher order elements may be implemented
5. FEM is simple compact and result oriented and hence widely popular among engineering community
6. Availability of large number of computer software packages and literature makes FEM a versatile and powerful numerical method

Disadvantages of FEM

1. Large amount of data is required as input for the mesh used in terms of nodal connectivity and other parameters depending on the problem
2. It requires a digital computer and fairly extensive
3. It requires longer execution time
4. Output result will vary considerably

Applications of FEM

For a particular application, several set of design of machines may need to be done to find the optimum designed machine. In finding the optimum design of the machine, much iteration may be required to incorporate the changes in parameters till the satisfactory performance design is obtained. These calculations with indefinite iterations are manually not possible. These calculations can be easily done by digital computers.

FEM allows detailed visualization of where structures bend or twist and indicates the distribution of stresses and displacements. FEM software provides a wide range of simulation options for controlling the complexity of both modelling and analysis of a system. Similarly, the desired level of accuracy and associated computational time requirements can be managed simultaneously to address most engineering applications. FEM allows entire designs to be constructed, refined and optimized before the design is manufactured.

New CAD Machine Software Using Finite Element

Replacement of existing 2D CAD tools with an advanced 3D CAD tool will allow the finite element to create an integrated 3D model of the complete system. This model will include complete definitions of the interfaces between all components of the system. The 3D CAD system reduces the duration of the design cycle by replacing a time consuming, error – prone, manual cross-checking process with an automated process that checks for interface mismatches between components. The 3D CAD model can also be used as the basis for FEA, eliminating the need to develop an additional model within the FEA tool.

The most successful design process consisted of generating the models for use in the FEA tool using the 3D CAD tool. Once the 3D CAD model was created, it was exported to the FEA tool for analysis. As the need for design modifications was revealed by the analysis, the model updates were performed in the 3D CAD tool and the model was re – exported to the FEA tool for further analysis.

This process has several benefits which includes;

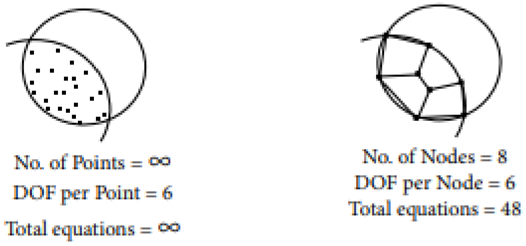
1. The design staff did not have to develop proficiency in using the model generation capabilities of the FEA tool
2. The design staff updated the models more efficiently with the more user - friendly 3D CAD tool user interface
3. Complete correlation between the design used for manufacturing and the design used for analysis eliminated errors introduced during creation of an independent FEA model

Success is attained upon achieving rapid and reliable transfer of 3D CAD models to the FEA tool. Two factors were found to have significant impact on model transferability.

i) **Model Complexity:** The designer required to pay attention to the model configuration needed by the FEA tool while creating the design in the 3C CAD tool. Within the 3D CAD model, the designer must segregate cosmetic features (i.e features not essential to equipment performance such as filters and chamfers) from structural features (i.e features that do impact the equipment performance). With appropriate segregation, the designer could exercise the feature suppression capabilities of the 3D CAD tool to simplify the model for analysis, a process known as idealization. Without idealization, the model presented to the FEA tool could be too complex for timely analysis. This requirement points to a need to develop guidelines for the design staff to ensure a model configuration amenable to de featuring.

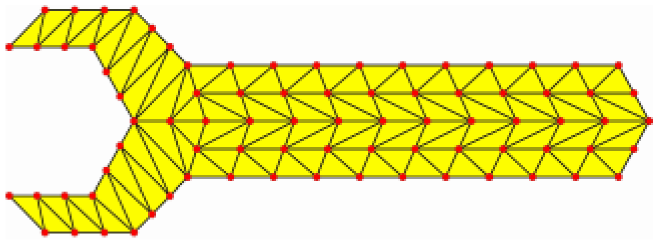
ii) **CAD – FEA model sharing:** The 3D CAD tool and the FEA tool support multiple data protocols for exportation and importation of data. Both support IGES, STEP and Parasolid transfer protocols. Model transfers using IGES were not successful. Model transfers using STEP were much better, but still not completely predictable and consistent results. The Parasolid format provided the most accurate and consistent results. The Parasolid format does introduce one complication; it converts all aspects of the design into metric units. When starting with a design based upon English units, the analyst must use caution in interpreting the analytical results, which will be presented in a metric format.

Meshing Process in FEA



The basic idea of FEA is to make calculations only at limited no. of points and then interpolate the results for the entire domain. Any continuous object has infinite degrees of freedom and it is just not possible to solve the problem in this format. FEM decreases the degrees of freedom from infinite to finite with the help of discretization or meshing.

Any physical object can be divided into a number of pieces with very small dimensions. These small pieces of finite dimension are called ‘Finite Elements’. Figure 4 shows a two-dimensional model of a spanner that has been so divided: the process is called discretisation, and the assembly of elements is called a **mesh**.



Elements can be of various shapes (as shown in Figure 5). It can be two dimensional (quadrilateral or triangular) or three-dimensional (brick-shaped (hexahedral), wedge-shaped (pentahedral) or tetrahedral). This is, of course, not a full list.

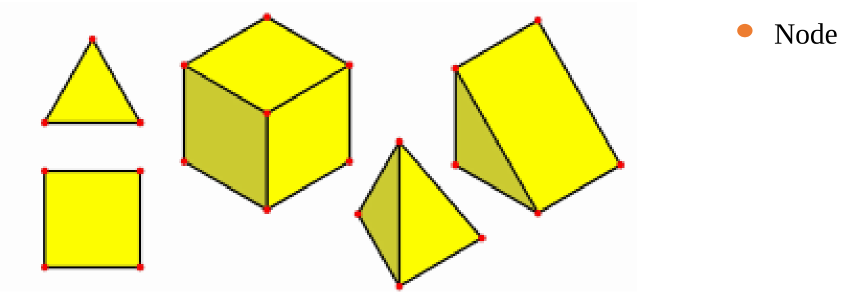


Fig. 5 Various finite elements commonly available

Thus the original domain is considered as an assemblage of number of such small elements. These elements are connected through number of joints which are called 'Nodes'. While discretizing the structural system, it is assumed that the elements are attached to the adjacent elements only at the nodal points. Each element contains the material and geometrical properties. The material properties inside an element are assumed to be constant.

The simple equations that model the finite elements are then assembled into a system of equations that models the entire problem.

Choosing a mesh having big elements reduces the accuracy of FEA. Choosing a mesh that is too small can critically increase the computation time required for the analysis. Therefore, choose a meshing technique that provides a good balance between accuracy, automation and computation time.

Gluing Function for the Analysis of FEA Tools

The limited interoperability between CAD and FEA systems becomes very evident during the idealization process that converts the CAD model to one suitable for FEA. After importing a 3D model from the CAD tool into the FEA tool, many parts must be **'glued'** together to provide constraints for the FEA tool when performing various types of analysis.

For example, structural steel shapes that are welded together must be glued in the FEA model as shown in fig. 6.

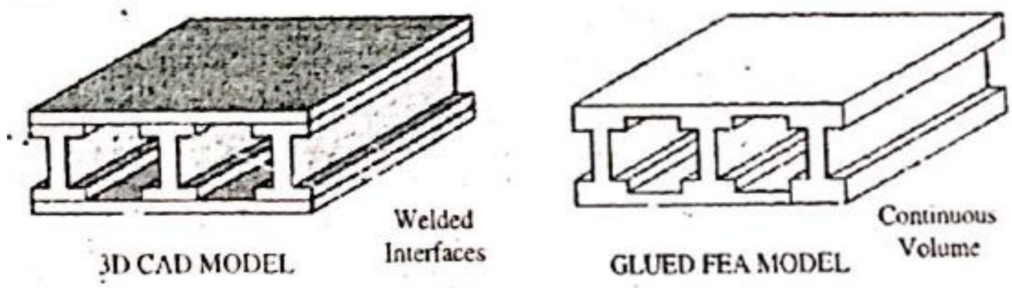


Fig. 6 Glue function

However, the data interoperability standards between the 3D CAD tool and the FEA tool do not include exchange of the glue information largely because these model constraints are not needed for CAD operations but are required for analysis.

<u>Ease of Use</u>

Usability was concern during the selection of FEA tool, but proved to be an even greater issue during the remainder of the project. At the time that the FEA tool was adopted by the SME, the FEA tool market was changing from a market of a few high – end tools to a split market that included high – end and low – end FEA tools.

FEA tools were following the pattern of 3D CAD tools; tools that were once expensive and targeted at specialists (high – end) were transforming to a simpler to use and less expensive FEA tools (low – end). The low - end tools also have limited functionality including less control over meshing and no ability to perform non – linear analysis.

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