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Design and Testing of Electrical Machines



M.V. Deshpande

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DESIGN AND TESTING OF ELECTRICAL MACHINES

M.V. Deshpande

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Preface

The main objective of this book is to present the subject of 'Design and Testing of Electrical Machines' in one volume to those studying for an engineering degree and also to junior engineers entering the field of electrical design in industry.

The first five chapters of the book deal with the principles of design of electrical machines, characteristics of magnetic, electric and insulating materials used in electrical machines, construction of electrical machines and design of magnetic and electric circuits.

The design of transformers is explained in Chapter 6. The procedure for designing transformers is explained and sample designs of distribution transformers, including an aluminium winding transformer and a power transformer, are worked out in detail. Chapter 7 gives the methods of carrying out various tests on transformers and keeping test records. The design of three-phase induction motors is dealt with in Chapter 8. Sample designs of squirrel cage induction motors with change in insulation from class A to class E, using the same frame, are completely worked out and compared with each other. One design for a slip ring induction motor is also worked out. Chapter 9 explains the various types of tests to be carried out on induction motors. Chapter 10 deals with the principles of designing single-phase induction motors; it works out one complete design and gives the tests required to be performed on single-phase motors. Chapter 11 deals with the design of synchronous generators. A commonly used type of diesel-driven alternator is designed. Chapter 12 explains in detail the various tests to be carried out on synchronous machines and the procedure for the preparation of test reports. The design of DC motors controlled by thyristor convertors is explained in Chapter 13. Sample designs of two DC motors are worked out in detail. Chapter 14 discusses the various tests to be carried out on DC motors. Chapter 15 describes the approach to the computer-aided design and compares it with the manual design procedure. It also discusses the method of design synthesis and programs for different machines and illustrates the computer-aided designs of three-phase induction motor and alternator with flow charts and actual design data sheets of

computer. Chapter 16 describes the basic theory and applications of stepper motors, rotating phase convertors, pole amplitude modulated (PAM) motors, reluctance motors and energy efficient motors.

The basic theory of transformers, three-phase induction motors, single-phase induction motors, synchronous machines and DC machines is dealt with in Appendices A to E to provide the background for design of the machines.

Throughout the book, emphasis has been placed on the use of Indian Standards Specifications for the design and testing of electrical machines and apparatus. Detailed steps of design, sample designs, modifications of designs and their effects on the operational characteristics, testing methods and keeping test records are explained in a simple and logical way. Problems of fault finding and maintenance are also highlighted.

Late Professor M.V. Deshpande taught this subject to B.E. students and postgraduate students for a number of years. In addition to his teaching and design experience, the author also kept in touch with industries engaged in designing and manufacturing of electrical machines. The author had very useful discussions with design engineers from various organisations.

Chapter 15 on “Computer Aided Design of Rotating Electrical Machines” and Chapter 16 on “Special Machines” were largely contributed by two highly experienced designers, Shri O.K. Kulkarni and Shri T.R. Mukundan, respectively, both of Jyoti Ltd. Baroda.

The book is the updated version of its previous second edition published by A.H. Wheeler & Co. Ltd., New Delhi. It is now republished as a new first edition. It is primarily aimed at undergraduate students of electrical engineering, both at degree and diploma levels. It will also be useful to AMIE students as well as to junior engineers in the industry entering the field of design and testing of electrical machines.

The publisher is thankful to Dr. M.A. Joshi, daughter of late Professor M.V. Deshpande, for painstakingly reading the proofs of this edition.

Publisher

Principles of Design of Electrical Apparatus

1.1 PRINCIPLES OF DESIGN

Building electrical equipment as economically as possible, to meet the performance expectations of the intended application, is of paramount importance to the manufacturers of electrical apparatus.

The main factors to be considered in the design of electrical apparatus are:

- (a) The choice of magnetic, electric and insulating materials used in apparatus. We have to consider the availability of each type of material, its characteristics, which must be consistent with the specifications and the performance limitations expected, and the cost.
- (b) The magnetic circuits in the apparatus.
- (c) The electrical circuits or the windings in the apparatus.
- (d) The insulation used in the apparatus.
- (e) Heating and cooling arrangements in the apparatus.
- (f) Mechanical design.

Limitations will be imposed on the design by a number of factors, such as saturation of magnetic circuits, insulation, temperature rise limitations expected, efficiency and specifications prescribed.

The art of design lies in suitable distribution of space to iron, copper, insulation and air in the machine or the apparatus. Economy in manufacturing costs, operating and running costs of the equipment should also be kept in view. One of the important criteria in good design is to get the minimum losses for a given total cost. If only the initial cost is considered and we try

to minimize it, this could result in a machine which may turn out to be expensive with regard to its recurring operating and maintenance costs. Besides the losses may be more. If we try to minimize the losses to get the maximum possible efficiency from the machine, it may turn out to be still costlier. There has, therefore, to be a balance between the losses and the cost, and the aim should be to obtain minimum losses (as per the required specifications) for a given total cost.

1.2 BASIC PRINCIPLES OF ELECTRICAL MACHINES

An electro-mechanical energy conversion device is a link between an electrical and a mechanical system. When the device acts as a generator, the mechanical system delivers energy through the device to the electrical system. When the device acts as a motor, the electrical system delivers energy through the device to the mechanical system. The process is reversible. Only that part of the energy which is converted to heat is lost and is not recoverable. An electrical machine can be made to work either as a generator or as a motor.

The electromechanical energy conversion depends on the interrelation between (i) the magnetic and the electrical fields, and (ii) the mechanical force and the motion. The basic points to be considered in the rotating machines are the production of induced voltages in the windings and the production of force and torque. In rotating machines, voltages are induced in the windings by rotating the windings mechanically in a magnetic field or by rotating the magnetic field past the windings. By either of these two methods the flux linkages with the windings are changed and voltages are induced.

Faraday's law states that voltage is induced in a coil proportional to the rate of change of flux linking the coil, that is

$$e = -N \frac{d\phi}{dt} \quad (1.1)$$

where N = number of turns in the coil; $\frac{d\phi}{dt}$ = rate of change of flux linking the coil.

When the emf is considered due to rotation of a coil in a magnetic field, it may be expressed as

$$e = B l v \text{ volts} \quad (1.2)$$

where B = flux density of magnetic field in Wb/m^2

l = length of conductor perpendicular to the magnetic field in metres

v = velocity of the conductor in m/s.

When considering the production of force, torque and power, the following basic relations hold good.

Mechanical force is exerted on a current carrying conductor in a magnetic field and is given by

$$F = B l I \text{ newtons} \quad (1.3)$$

where B = flux density in Wb/m^2

I = current in amps

l = length of conductor perpendicular to magnetic field in metres.

If a conductor on a rotor with radius r metres is considered, the torque produced by the current in the conductor is given by

$$T = F \times r = B l I r \text{ newton-metres} \quad (1.4)$$

This torque is electromagnetic torque.

$$\begin{aligned} \text{Power} &= \text{Torque} \times \text{Angular velocity of rotation per second } (\omega_r) \\ &= T\omega_r \end{aligned} \quad (1.5)$$

The generator and the motor actions go hand in hand. Both of them have current carrying conductors in the magnetic fields; also the conductors and the flux are travelling with respect to each other at a definite speed. Hence, in a rotating machine, voltage due to rotation and torque are produced. Only the direction of power flow will show whether the machine is working as a generator or as a motor.

In a generator armature

- (i) EMF E is induced just sufficient to overcome the drop of volts due to the resistance of the winding and to supply the load at the required voltage.
- (ii) Electromagnetic torque produced by the current carrying conductors in the armature is the counter torque opposing rotation.

In a motor armature

- (i) Rotational emf or speed voltage is produced in opposition to the applied voltage; this is known as counter emf or back emf.
- (ii) Mechanical torque is produced as required by the load driven by the motor.

Thus, electromechanical energy conservation is a reversible process.

1.3 TYPES OF ELECTRICAL MACHINES AND THEIR CHARACTERISTICS

The main types of electrical machines are: (a) Synchronous machines, (b) Induction machines and (c) DC machines.

- (a) A *synchronous machine* has a coil winding on the rotor and a three-phase winding on the stator. The rotor winding is supplied by a dc source. This coil winding on the rotor produces a field and with the rotation of the rotor, the field will move in space at the speed of the rotor. Voltage will thus be induced in the stator three-phase winding. The magnitude of this induced voltage depends on the strength of the dc field and its frequency corresponds to the speed of the rotor when it is driven as a generator. In the case of motor action, three-phase current is supplied to the stator winding. This produces a rotating field in the air gap. This rotating field reacting with the dc field produced by the current in the rotor, makes the machine run as a motor at synchronous speed. In small machines, the construction may have a rotating armature and the field winding on stationary poles.
- (b) An *induction machine* has a polyphase winding on both the stator and the rotor. The three-phase winding on the stator produces a rotating magnetic field which is cut by the closed circuit of the rotor, thereby producing an induced voltage in the rotor

winding due to transformer action. This produces current in the rotor winding which reacts with the flux to produce torque. The machine runs as an induction motor on the induction principle.

- (c) A dc machine has a stationary coil winding wound on poles, which produces a field stationary in space in the air gap due to direct current fed to the field winding. The armature (rotor) has a commutator type winding with stationary brushes for connection with the external circuit.

1.3.1 Basic Characteristics of Electrical Machines

The design of electrical machines involves the study of:

- (a) The voltages induced in the windings, the load currents and terminal voltages under different loading conditions.
- (b) The power (input or output) received or given out by the machine.
- (c) The speed at which the machine is running under different loading conditions—frequency.
- (d) The torque produced under different loading conditions.

Interrelations between the above quantities for a machine running as a generator or motor can be worked out for different types of electrical machines. These relations decide the suitability of a particular type of machine for a particular application.

Designing an electrical machine consists of choosing the proper size and dimensions of the machine parts. To get the required performance, the appropriate magnetic and the electrical circuits must be calculated and set. Then knowing the details of circuit parameters and the dimensions of the various parts of the machine, the performance of the machine can be predetermined by calculations. The machine can be represented by an equivalent circuit and its performance can be determined under different operating conditions.

The characteristics of the machine can be also found out by actual tests. The accuracy of a design will be seen by checking how close the predetermined calculated performance of the machine is to the actual test results when the machine is tested after it is built as per design calculations.

In case there is a difference between the predetermined performance of the machine and the test results, it is necessary to find out the reasons for it and modify the design so that the performance of the machine built from the modified design will work up to the requirements.

1.4 SPECIFICATIONS

The majority of the electrical machines manufactured today are as per standard specifications. The Bureau of Indian Standards (BIS) has prepared standards for various types of electrical equipment and machines to cover the requirements of the consumers. The designs of various machines have to conform to the standard specifications to suit the end requirements. Standardization helps in economy and in the comparison of performance within the given limits.

Standards have been set for various types of motors, for transformers giving the main output requirements, for conditions under which the equipment will operate (e.g. voltage, rating, frequency of supply, type of connections of windings) and in the case of rotating machines, the

speed of rotation, torque produced under different operating conditions, such as full load, maximum torque, starting torque, etc. The type of enclosure of the machine: open or totally enclosed or other type is also standardized.

Maximum permissible temperature rise is a very important limitation prescribed by the standards. It will depend on the type of the insulation used in the construction of the machine.

The rating of the machine can be continuous or for a short time. Continuous rating will be the continuous load on the machine while running; the short time rating of a machine will be its rating when run for some specified time, e.g. 1 hour or 1/2 hour. If the machine is stopped for some time and again run for a similar period the rating is called the intermittent rating of the machine.

The frame sizes in which electrical machines are built are standardized. The general layout and dimensions of the machines—particularly industrial motors—are also standardized so that it is easy to replace the equipment in the same location.

The various Indian Standards should be used while designing the equipment, and also the consumers while ordering equipment should mention the standards to which the equipment should be built and the degree of the expected performance accuracy.

The performance criteria will mention the operation of the equipment under full load, percentage loads, speed, losses, efficiency, torques, current, temperature rise, etc. The details will be mentioned while designing each type of equipment such as transformers, synchronous machines, induction motors, dc machines, etc. The methods and the apparatus for testing the various types of electrical machines will be explained in the section following the design principles and design calculations.

1.5 RATING AND DIMENSIONS OF ELECTRICAL MACHINES

The rating of ac machines is expressed in kVA output for generators and kVA input for motors. In the case of dc machines, the rating is given in kW output for the generators and kW input for motors. For transformers, the rating is in kVA output.

The main dimensions in case of rotating machine are the diameter of the stator bore and the length of the stator core. The relation between the output of a machine and these main dimensions can be seen as follows:

Let D = diameter of the stator bore in metres
 L = stator core length in metres
 p = number of poles
 n = speed in revolutions per second
 S = electrical rating of the machine in kVA
 E_{ph} = voltage per phase
 I_{ph} = current per phase

$$E_{ph} = 4.44 K_w f T_{ph} \phi_m \text{ volts} \quad (1.6)$$

where K_w = winding factor

f = frequency in Hz

T_{ph} = number of turns in series per phase

ϕ_m = flux in the air-gap.



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designer is 'which D and L of the machine will give the required D^2L product?' The speed n may be limited to about 100 m/s. For forged steel rotors of turbo alternators this may be as high as 140 m/s. For standard motors, the speed is generally 30 m/s. This limits the size of the diameter. The aim of the designer would be to make the diameter as small as possible to make the machine more compact.

1.5.3 Output Coefficient

This is defined as the ratio of output to D^2Ln . The output coefficient

$$G = S/D^2Ln = 11 K_w \bar{B} \times ac \times 10^{-3} \quad (1.10)$$

In a motor, if the mechanical output is given in terms of metric horsepower, then the output in kW = 0.736 × HP (metric) and the rating is

$$\text{input kVA} = \text{kW output} / \eta \cos \phi \quad (1.11)$$

where η = efficiency; $\cos \phi$ = power factor.

1.5.4 Output and Output Coefficient of DC Machines

The emf induced in the armature of a dc machine is given by

$$E = \frac{\phi Z np}{a} \text{ volts} \quad (1.12)$$

where

ϕ = flux per pole

Z = number of conductors

$$\phi = \bar{B} Y L = \bar{B} \pi D L / p$$

$$ac = \frac{I Z}{a \pi} D$$

$$\text{The output in kW, } P = EI \times 10^{-3}$$

Substituting the values of E and I ,

$$P = \text{output in kW} = \pi^2 \bar{B} \times ac \times D^2 L n \times 10^{-3} \quad (1.13)$$

$$\text{The output coefficient, } G = \frac{\text{Output } P}{D^2 L n}$$

or

$$G = \pi^2 \bar{B} \times ac \times 10^{-3} \quad (1.14)$$

Choosing B and ac , the diameter D and core length L can be determined for a given output of a dc generator running at known speed. In the case of a dc motor, the input will be considered, the efficiency expected will be taken into account and the induced emf will correspond to the back emf in the armature at the rated load current.

It will be seen that the output depends on the product of D^2L dimensions of the machines. The dimensions D and L for a machine are shown in Figure 1.1.

In case of induction motors, the core length may be approximately taken equal to pole pitch, i.e. $L = Y = \pi D/p$ and then D and L can be determined separately from the D^2L product.

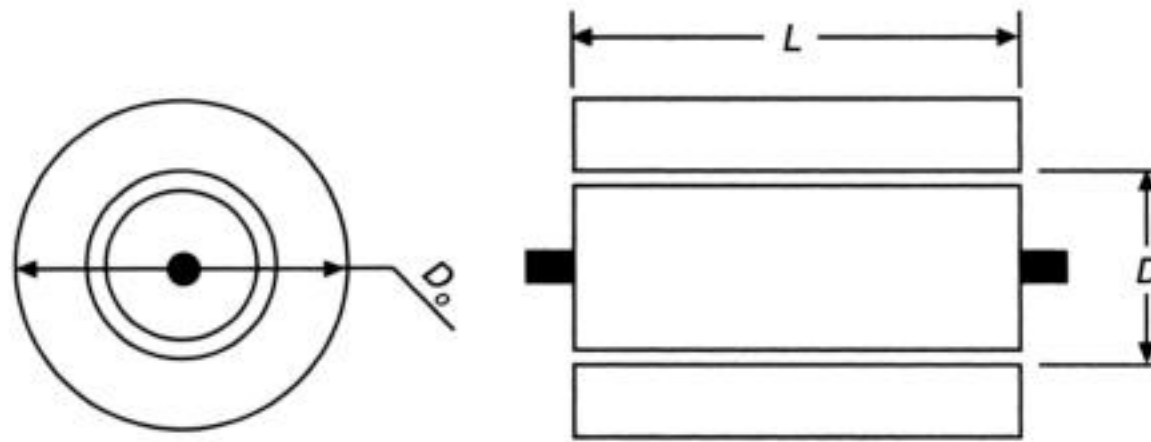


Figure 1.1 D and L dimensions of a machine.

EXAMPLE 1.1 Find the main dimensions D and L of an induction motor with the following data:

20 HP (metric), 415 volts, three-phase, 50 Hz, 4-pole induction motor; efficiency 85%; power factor 0.85 lagging; winding factor may be taken as 0.95.

Solution:

Input kVA

$$S = \frac{\text{Output in kW}}{\text{Power factor} \times \text{Efficiency}}$$

$$= \frac{20 \times 0.736}{0.85 \times 0.85} = 20.375$$

Choose specific magnetic loading $\bar{B} = 0.55 \text{ Wb/m}^2$ and specific electric loading $ac = 35,000$ ampere-conductors/m

$$S = 1.11 K_w \pi^2 \bar{B} \times ac \times D^2 L n \times 10^{-3}$$

n = speed in rps; poles = 4 as $f = 50 \text{ Hz}$

$$\frac{pn}{2} = f; \frac{4 \times n}{2} = 50 \text{ or } n = 25 \text{ rps (1500 rpm)}$$

Substituting the values of $\bar{B}$, ac , and n in the expression for the rating of the motor in kVA,

$$20.375 = 1.11 \times 0.95 \times \pi^2 \times 0.55 \times 35,000 \times D^2 L \times 25 \times 10^{-3}$$

Solving, $D^2 L = 4068 \text{ cm}^3$.

If the length of the core L is made equal to pole pitch, then

$$L = Y = \frac{\pi D}{p} = \frac{\pi D}{4}$$

$$D^2 L = \frac{\pi D^3}{4} = 4068 \text{ cm}^3$$

$$D^3 = \frac{4068 \times 4}{\pi} = 5179 \text{ cm}^3$$

Therefore, $D = \sqrt[3]{5179} = 17.30 \text{ cm}$; say $D = 17.5 \text{ cm}$

$$L = \frac{4068}{17.5^2} = 13.28; \text{ say } 13.5 \text{ cm}$$

The main dimensions of the induction motor therefore are:

Stator bore diameter = 17.5 cm

Length of stator core = 13.5 cm

EXAMPLE 1.2 Find the main dimensions D and L of the synchronous generator having the following data:

625 kVA, three-phase, 50 Hz, 3300 volts, 0.8 power factor lagging, 10-pole synchronous generator driven by a diesel engine. The winding factor K_w may be taken as 0.96.

Solution:

Being a 10-pole machine, the speed is given by

$$\frac{10 \times n}{2} = 50 \text{ or } n = 10 \text{ rps (600 rpm)}$$

The output rating of the generator

$$S = 625 = 1.11 \times 0.96 \times \pi^2 \times \bar{B} \times ac \times D^2 L n \times 10^{-3} \text{ kVA}$$

Choosing the value of $\bar{B} = 0.8 \text{ Wb/m}^2$ and $ac = 40,000$ ampere-conductors/m; substituting and solving,

$$D^2 L = 185.70 \times 10^3 \text{ cm}^3$$

Taking the length of the core = pole pitch $= \frac{\pi D}{p} = \frac{\pi \times D}{10}$

$$\frac{\pi D^3}{10} = 185.70 \times 10^3 \quad \text{or} \quad D^3 = 591,101 \text{ cm}^3$$

Therefore, $D = 84 \text{ cm}$

$$L = \frac{185.70 \times 10^3}{84^2} = 26.3 \text{ cm}; \text{ say } L = 26.5 \text{ cm}$$

The main dimensions of the synchronous generator therefore are:

Stator bore diameter = 84 cm

Length of stator core = 26.5 cm

EXAMPLE 1.3 Calculate the main dimensions D and L of a 50 kW, 230 volts, 900 rpm, 6 pole dc shunt motor. Take the emf induced in the armature E_b as 220 volts and efficiency as 87%.

Solution:

$$\text{Current } I = \frac{50 \times 1000}{230 \times 0.87} = 250 \text{ A}$$

$$P = EI = 10^{-3}$$

$$= 220 \times 250 \times 10^{-3} = 55 \text{ kW}$$

Take $\bar{B} = 0.6 \text{ Wb/m}^2$; $ac = 30,000$ ampere-conductors per m;

$$P = \pi^2 \bar{B} \times ac \times D^2 L n \times 10^{-3}$$

Substituting the values,

$$55 = \pi^2 \times 30,000 \times D^2 L \times \frac{900}{20} \times 10^{-3}$$

Solving,

$$D^2 L = 0.02 \text{ m}^3 = 20,000 \text{ cm}^3$$

If the length of the core is made $L = \frac{2}{3}$ pole pitch

$$= \frac{2}{3} \times \frac{\pi D}{6} = \frac{\pi D}{9}$$

$$D^2 L = \frac{\pi D^3}{9} = 20,000$$

$$D^3 = \frac{20,000 \times 9}{\pi} = 57,296 \text{ and } D = 38.55 \text{ cm; say } 40 \text{ cm}$$

$$L = \frac{20,000}{40^2} = 12.5$$

The main dimensions of the DC shunt motor are, therefore, given by

$$D = 40 \text{ cm; } L = 12.5 \text{ cm.}$$

Frame sizes: Frame sizes are standardized so that a number of combinations of speed (poles), frequency, rating, and output are possible. Standard frame sizes are designed in practice and used so that the manufacturer may use each frame for one or two gap diameters and different lengths. Generally lengths may be normal ones, or shorter than these up to 70% or longer than normal by about 20% to 30%. Frame sizes with overall diameter D_o and short (S), medium (M) or long (L) lengths for the same D_o are shown in Figure 1.2.

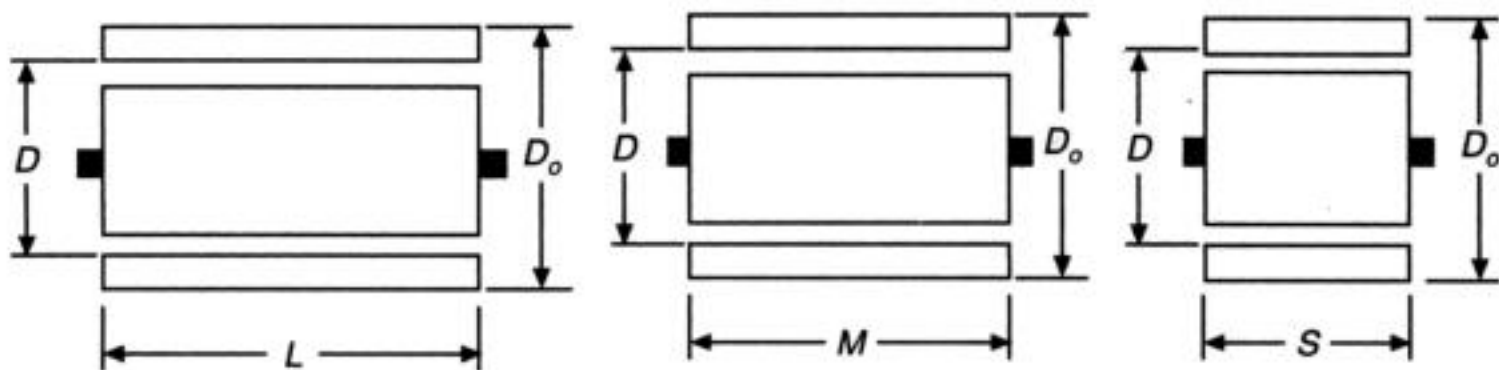


Figure 1.2 Frame size with L , M and S length of cores.

1.6 HEATING AND COOLING OF MACHINES AND APPARATUS

Due to energy losses in a machine, it gets hot. Cooling is the function of the facilities for dissipation of heat produced in the machine so that it can work satisfactorily within the required temperature limit. The temperature rise depends on the relation between heat produced and the heat dissipated due to cooling arrangements. The final temperature rise is reached when the rates of heat production and heat dissipation are equal.

Heat dissipation is by radiation, conduction and convection. For small machines, natural cooling is relied on, i.e. convection and radiation. For larger machines, fans are fixed on the rotor and definite air flow is produced through ducts, etc. For very large machines, external means of cooling are used. Most transformers are oil immersed: heat from the coils and cores is conducted to the oil, then it travels to the tank walls by conduction and convection, and the tank walls dissipate it to the outside air by convection and radiation.

The main types of cooling systems are:

- (a) *Open circuit cooling:* This is a method of cooling in which the coolant is drawn from the medium surrounding the machine, passes through the machine and then returns to the surrounding medium.
- (b) *Closed circuit cooling:* This is a method of cooling in which a primary coolant is circulated in a closed circuit through the machine, and, if necessary, through a heat exchanger. Heat is transferred from the primary coolant to the secondary coolant either through the structural parts or through the heat exchanger.
- (c) *Air cooling:* In this system, only air is relied upon for cooling the windings, core and other working parts.
- (d) *Hydrogen cooling:* In this system, no medium other than hydrogen is relied upon for cooling windings, core and other working parts of the machine.
- (e) *Liquid cooling:* In this system, liquid is relied upon for cooling the windings, core and other working parts of the equipment. The part may be either cooled by immersion in liquid or by circulation of liquid through it.
- (f) *Direct cooling:* In this system, the coolant comes in direct contact with conductors/part to be cooled.

1.6.1 Heat Dissipation due to Radiation

For a small spherical radiating body inside a large and/or black spherical cavity, loss due to radiation may be obtained by the Stefan-Boltzmann law:

$$P \text{ due to radiation} = 5.7e (T_1^4 - T_2^4) \times 10^{-8} \text{ watts/m}^2 \quad (1.15)$$

where e = emissivity.

$$T_1 = (\theta_1 + 273)^\circ\text{C}$$

$$T_2 = (\theta_2 + 273)^\circ\text{C}$$

A transformer tank in a substation may be considered a small spherical body radiating heat and the heat radiated from the transformer tank can be approximately calculated by the use of Eq. (1.15).

A motor body may also be approximately considered in the same way in a shop and the heat radiated may be approximately found out.

1.6.2 Air Cooling

Knowing the loss to be dissipated, and the temperature rise of the cooling medium, it is possible to find out the amount of cooling medium required, e.g. air and also the fan power required to circulate the required air through the apparatus for cooling purposes.

If P = heat loss to be dissipated in kW

θ = temperature rise of cooling air in °C

θ_1 = inlet temperature of air in °C

p = pressure in newtons/m²

Q = volume of air in cubic metres/second

H = barometric height in mm of Hg

The specific heat of dry air at constant pressure is 0.2375.

1 kg of dry air has a volume of $0.775 \frac{(\theta_1 + 273)}{273} \frac{760}{H}$ cubic metres

1 kW = 240 cal per second.

1 kW loss raises the temperature of $\frac{240}{237.5} = 1.01$ kg of air by 1°C per second. Therefore, the volume of air required for P kW of loss to be dissipated is given by

$$Q = 0.78 \times \frac{P}{\theta} \times \frac{\theta_1 + 273}{273} \times \frac{760}{H} \text{ cubic metres/second} \quad (1.16)$$

If this air flow is supplied by a fan at a pressure p newtons per m² and the fan has efficiency η , then the power required for the fan to provide this quantity of air is given by

$$P_{\text{fan}} = \frac{pQ}{\eta \times 10^3} \text{ kW} \quad (1.17)$$

A similar principle applies to cooling systems when the cooling medium is gas or hydrogen; here the thermal conductivity, density and specific heat should be taken into consideration.

EXAMPLE 1.4

- Calculate the volume of cooling air in cubic metres/second required to carry off the losses in a 10 MW generator having an efficiency of 97.5%. The inlet and outlet temperatures of air may be taken as 15°C and 35°C respectively. Barometric height is 750 mm.
- Find the power required to drive the fan to provide this circulation of air at a pressure of 1000 N/m². Efficiency of fan = 30%.



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1.7 TEMPERATURE RISE DUE TO THERMAL ACTION

An electric machine or a transformer can be considered as a homogeneous body in which heat is internally developed at a uniform rate and heat dissipation is at a rate proportional to its temperature rise. The relation between the temperature rise and time is an exponential function.

- Let p = heat developed in the apparatus in watts or joules/second
 c_p = specific heat in joules per kg per °C
 G = weight of machine active parts in kg
 θ = temperature rise in °C
 ϕ_m = maximum temperature rise in °C
 t = time in seconds
 s = cooling surface in m²
 λ = specific heat dissipation or emissivity in joules per second per m² of cooling surface per °C difference between the surface and the ambient temperature of the cooling medium.
 $c = 1/\lambda$ = cooling coefficient
 τ = heating time constant in seconds
 τ' = cooling time constant in seconds.

In a specific short time dt , the heat produced in the machine = $p dt$. Out of this, the machine will store heat = $G c_p d\theta$ if the temperature rise in time dt is $d\theta$. Heat dissipated = $S\lambda \theta dt$.

Heat produced = Heat stored + Heat dissipated

$$p dt = G c_p d\theta + S\lambda \theta dt$$

$$\frac{p}{G c_p} = \frac{d\theta}{dt} + \theta \frac{S\lambda}{G c_p}$$

when $t = 0$, $\theta = 0$; when $t = \infty$, $\theta = \theta_m = \frac{p}{S\lambda}$

Solving the differential equation,

$$\theta = \theta_m (1 - e^{-t/\tau}) \quad (1.21)$$

where τ is the heating time constant. It is the time during which the apparatus will reach 0.632 times the maximum temperature rise.

$$\text{The value of } t = G c_p / S\lambda \quad (1.22)$$

The nature of the temperature vs. time relation is shown in Figure 1.3. This relation can be found out for the windings, core, frame or total machine.

1.7.1 Cooling of Machines

When there is reduction in losses or the machine stops and thereby losses are not there, the temperature of the apparatus will go down and the curve of temperature vs. time will be an exponential curve which will be the heating time curve inverted; the rate of heat dissipation—cooling—is, however, different; this is τ' cooling time constant and

$$\theta = \theta_m e^{-(t/\tau')} \quad (1.23)$$

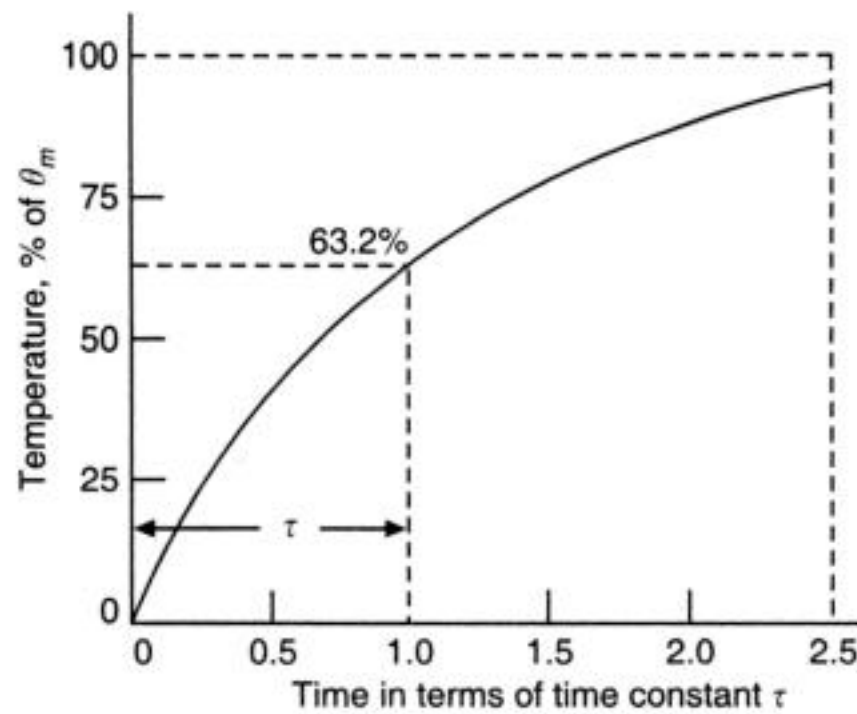


Figure 1.3 Temperature rise vs. time curve.

Cooling coefficient: If it is assumed approximately that the cooling is proportional to the temperature drop, the maximum temperature reached by a continuous rated machine is

$$\theta_m = p/S\lambda = cp/S \quad (1.24)$$

where c = cooling coefficient = $\frac{1}{\lambda}$

The application of heating time constants and temperature rise calculations can be shown by the following examples.

EXAMPLE 1.5 At the beginning of the loading of a transformer, its temperature is 25°C . After running for 2 hours on full load the temperature is 55°C and after running for 4 hours it is 70°C . Calculate:

- The heating time constant.
- The maximum final temperature rise with full load on the transformer.
- The time it will take after the start for the transformer to reach 5/6th of its final steady-state temperature.

Solution:

- Let θ_m = maximum temperature rise in $^\circ\text{C}$
 τ = heating time constant in hours

After 2 hours, the temperature rise is $55 - 25 = 30^\circ\text{C}$

After 4 hours, the temperature rise is $70 - 25 = 45^\circ\text{C}$

The following relations can, therefore, be written.

$$30 = \theta_m(1 - e^{-2/\tau}) \quad (i)$$

$$45 = \theta_m(1 - e^{-4/\tau}) \quad (ii)$$

From (i) and (ii),

$$\frac{45}{30} = \frac{1 - e^{-4/\tau}}{1 - e^{-2/\tau}} = 1 + e^{-2/\tau} = 1.5$$

$$\begin{aligned} \text{or} \quad e^{-2/\tau} &= 0.5 \\ \text{or} \quad -2/\tau &= -0.69 \\ \text{or} \quad \tau &= 2.9 \text{ h} \end{aligned}$$

$$(b) \quad \theta_m = \frac{30}{1 - 0.5} = 60^\circ\text{C}$$

$$(c) \quad 5/6\text{th of the maximum temperature rise} = 60 \times \frac{5}{6} = 50^\circ\text{C}$$

It can, therefore, be written

$$\begin{aligned} 50 &= 60(1 - e^{-t/2.9}) \\ \text{or} \quad 1 - e^{-t/2.9} &= 5/6 \quad \text{or} \quad e^{-t/2.9} = 0.1666 \end{aligned}$$

$$\text{or} \quad \frac{t}{2.9} = 1.79 \quad \text{or} \quad t = 1.79 \times 2.9 = 5.19 \text{ h}$$

The transformer will, therefore, reach the temperature rise of 50°C in 5.19 hours.

EXAMPLE 1.6 A motor has a thermal heat time constant of 45 minutes. When the motor runs at its continuous rating, its final temperature rise is 75°C . (a) What is the temperature rise after 1 hour if the motor runs continuously on this load? (b) If the temperature rise at one hour rating is 75°C , find the maximum steady temperature at this rating. (c) How much time does the motor take for its temperature to rise from 50°C to 75°C if it is working at its one hour rating?

Solution:

$$(a) \quad \text{Heating time constant} = 45 \text{ min} = 0.75 \text{ h}$$

$$\theta = 75(1 - e^{-1/0.75})$$

$$\theta = 75(1 - 0.285) = 75 \times 0.715 = 53.625^\circ\text{C}$$

$$(b) \quad 75 = \theta_m(1 - e^{-1/0.75})$$

$$\theta_m = \frac{75}{0.715} = 104^\circ\text{C}$$

$$(c) \quad \text{Time for the temperature to rise to } 75^\circ\text{C, is 1 hour. Time for the temperature rise to } 50^\circ\text{C with the motor running at one hour rating,}$$

$$50 = 104(1 - e^{-t/0.75})$$

$$0.48 = 1 - e^{-1.33t}$$

$$e^{-1.33t} = 0.52; \quad -1.33t = -0.654 \quad \text{or} \quad t = 0.4915 \text{ h} = 29.5 \text{ min}$$

Therefore, the time for the transformer's temperature to rise from 50°C to $75^\circ\text{C} = 60 - 29.5 = 30.5 \text{ min}$.

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Table 2.1 Hot rolled electrical sheet steel dynamo grades

<i>Grade</i>	<i>Lohys</i>	<i>Special Lohys</i>	<i>Medium resistance</i>	<i>42 Quality</i>
Density, g/cc	7.82	7.78	7.72	7.67
Silicon %, approx.	0.3	0.85	1.75	2.5
Resistivity, $\mu\Omega/\text{cm}^3$	15	21	33	41
Temperature coefficient of resistance per °C	0.00338	0.00250	0.00165	0.00137
Stacking factor % (0.50 mm thick uninsulated sheets)	95	95	95	95
Weight in kg per sq. metre	39.74	39.5	39.20	38.86
Maximum total iron loss for 0.50 mm thick sheets at $B_{\text{max}} = 1$ tesla at 50 Hz, in W/kg	3.57	2.84	2.51	2.25

Table 2.2 Hot rolled transformer grades

<i>Grade</i>	<i>Grade 92</i>	<i>Grade 86</i>	<i>Grade 80</i>	<i>Grade 74</i>
Density, g/cc	7.55	7.55	7.55	7.55
Silicon %, approx.	4.0	4.0	4.0	4.0
Resistivity, $\mu\Omega/\text{cm}^3$	60	60	60	60
Temperature coefficient of resistance per deg. °C	0.00075	0.00075	0.00075	0.00075
Stacking factor % (0.35 mm thick uninsulated sheets)	92	92	92	92
Weight in kg/sq. metre	26.85	26.85	26.85	26.85
Maximum total iron loss for 0.35 mm thick sheets at $B_{\text{max}} = 1.3$ tesla, 50 Hz, in W/kg	2.02	1.89	1.76	1.63

Table 2.3 Cold rolled grain-oriented transformer grades

<i>Grade</i>	<i>Grade 51</i>	<i>Grade 46</i>	<i>Grade 41</i>
Thickness	0.35 mm	0.30 mm	0.28 mm
Density, g/cc	7.65	7.65	7.65
Silicon %, approx.	3.1	3.1	3.1
Resistivity, $\mu\Omega/\text{cm}^3$	48	48	48
Stacking factor %	97	97	97
Maximum total iron loss at $B_{\text{max}} = 1.5$ tesla at 50 Hz stress relief annealed after cutting, in W/kg	1.11	0.97	0.89

Grades of steel sheets to be used in rotating machines and transformers are selected considering the requirements of the permissible losses and the relative costs of the material. For rotating machines, dynamo grades of hot rolled steel are used. For transformers, transformer grades of hot rolled steel are commonly used; where lower losses are required, cold rolled grain-oriented sheet steel of the required grade may be used.

Where available, ratio transformer grades of sheet steel are used in applications where good permeability is required at low flux densities. These transformer grades should have good punching properties and be capable of being fabricated satisfactorily. The applications include audio frequency transformers and reactors for the electronic industry. In the U.S.A., for example, United States Steel have USS radio transformer grade 58 and USS radio transformer grade 65 specially made for these purposes. These grades are rated by their dc permeability at 10^{-2} tesla as measured by the Fahy permeameter method. USS radio transformer 58 has a minimum permeability of 1800 and USS radio transformer 65 has a minimum permeability of 1500 when tested in 'as sheared' condition. These grades are not supplied on maximum core loss limit considerations but on permeability considerations.

2.2 CHARACTERISTICS OF MAGNETIC MATERIALS

In designing electrical apparatus, core loss and other magnetisation characteristics of the core material are considered. Core loss varies with maximum induction density, frequency and the thickness of the magnetic material. For each thickness of the material, the curves of the core loss vs. induction and core loss vs. frequency should be known. In addition, the magnetisation characteristics of the material should be known. The following types of curves have been determined and are available when designing electrical apparatus using each type of magnetic material.

- (a) *Core loss vs. induction curve:* This is a curve showing the total iron loss in watts per kg vs. peak or maximum induction in tesla or Wb/m^2 . A typical curve for special Lohys, 0.5 mm thick magnetic stampings is shown in Figure 2.1. This magnetic material is used in cores of rotating machines. Knowing the weight of the part of the machine where this material is used, the total iron loss in the material when operated at calculated flux density or induction is obtained from the curve in terms of watts per kg weight of the material working at the calculated B_{max} .

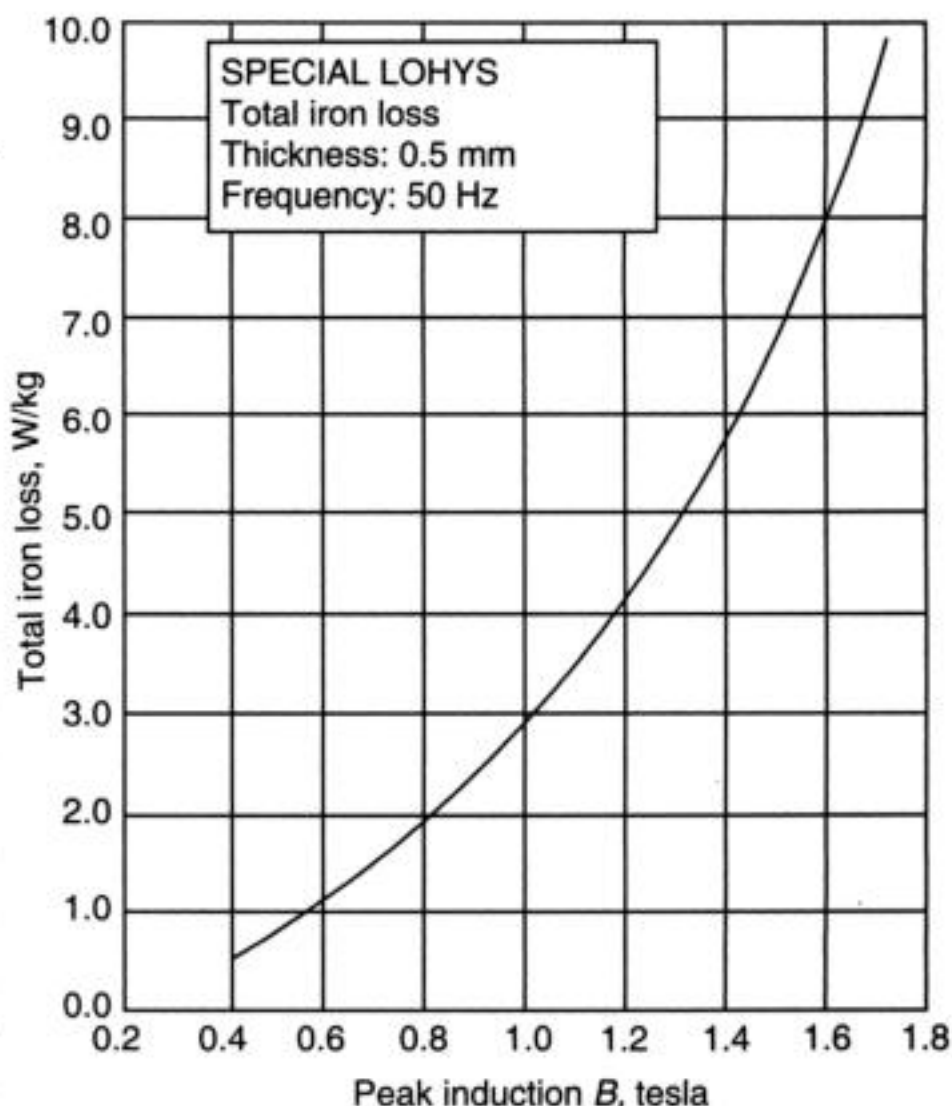


Figure 2.1 Total iron loss in W/kg vs. peak induction in tesla (Special Lohys).

Figure 2.2 shows a similar curve of total iron loss in W/kg vs. peak induction in tesla for grade 51 electrical sheet steel which is cold rolled steel. It may be observed here that when the loss is tested with flux parallel to the rolling direction, it is less than that with flux transverse to the rolling direction. Grade 51 is 0.35 mm thick stampings which are used for transformers. Figure 2.2(a) shows the curve for grade 41 stampings.

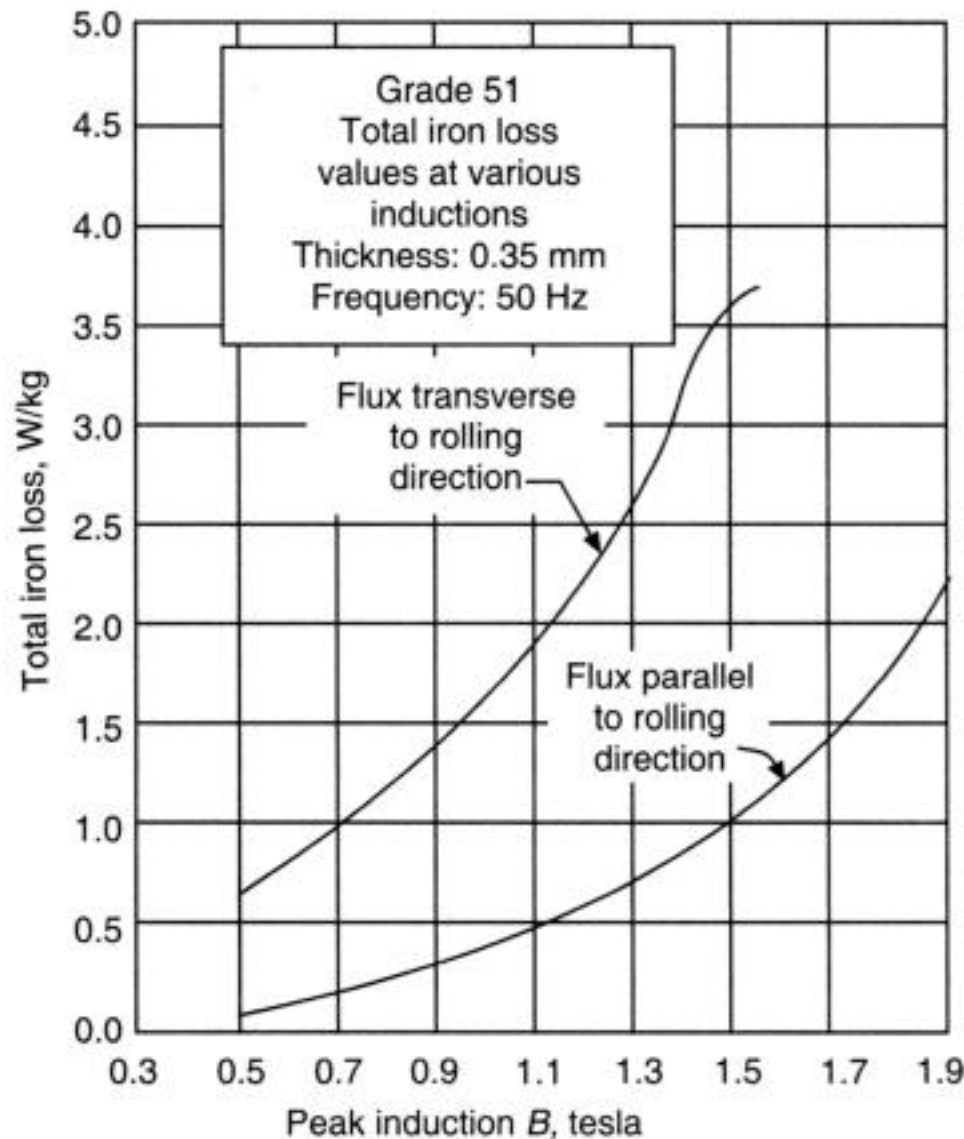


Figure 2.2 Total iron loss in W/kg vs. peak density in tesla (grade 51).

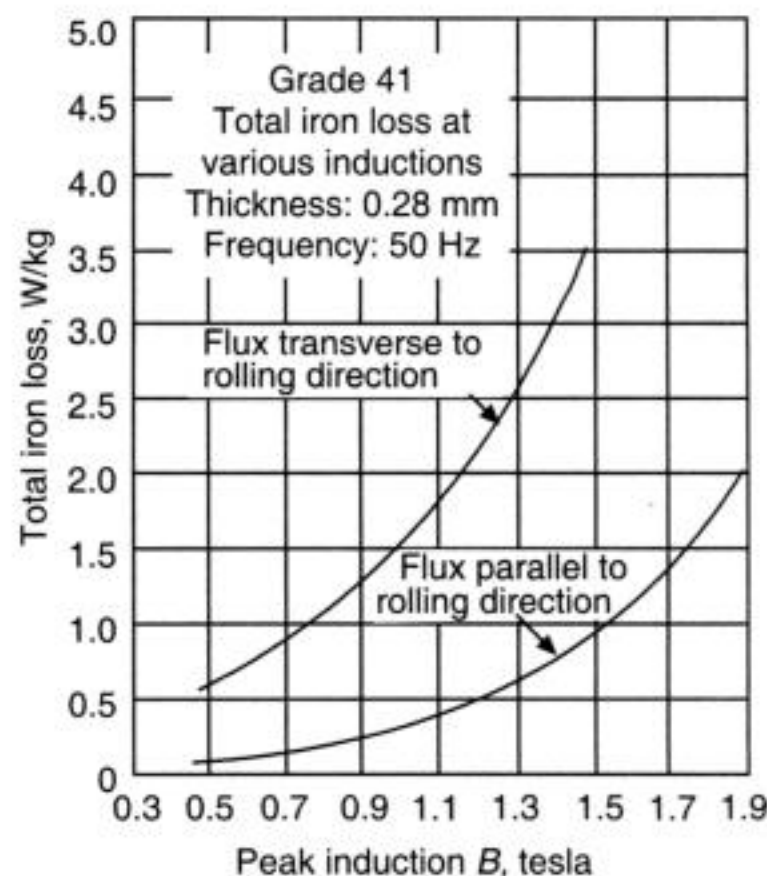


Figure 2.2(a) Total iron loss in W/kg vs. peak density in tesla (grade 41).



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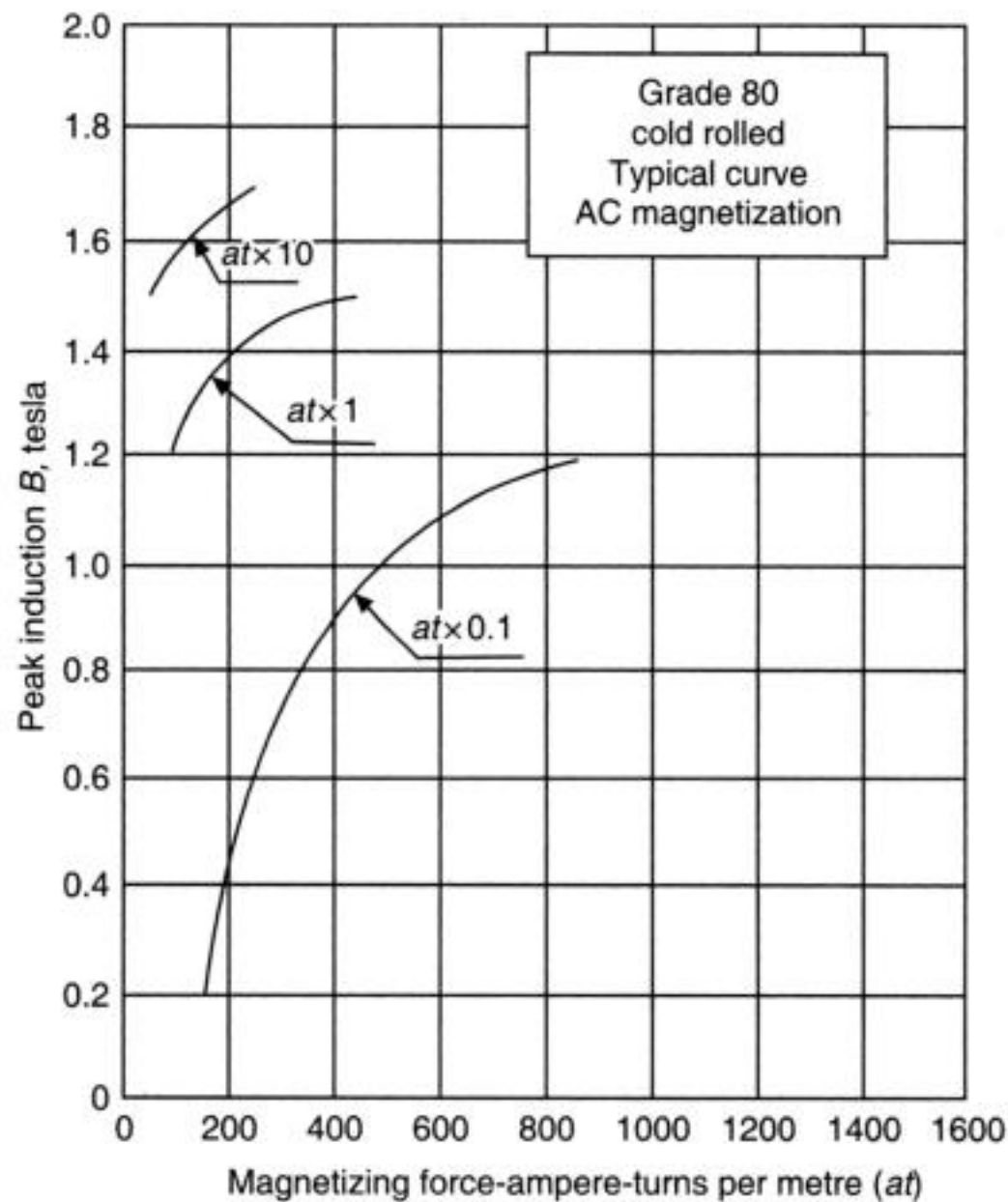


Figure 2.3(a) AC magnetization curve—peak induction density in tesla vs. magnetizing force in ampere-turns per metre (grade 80).

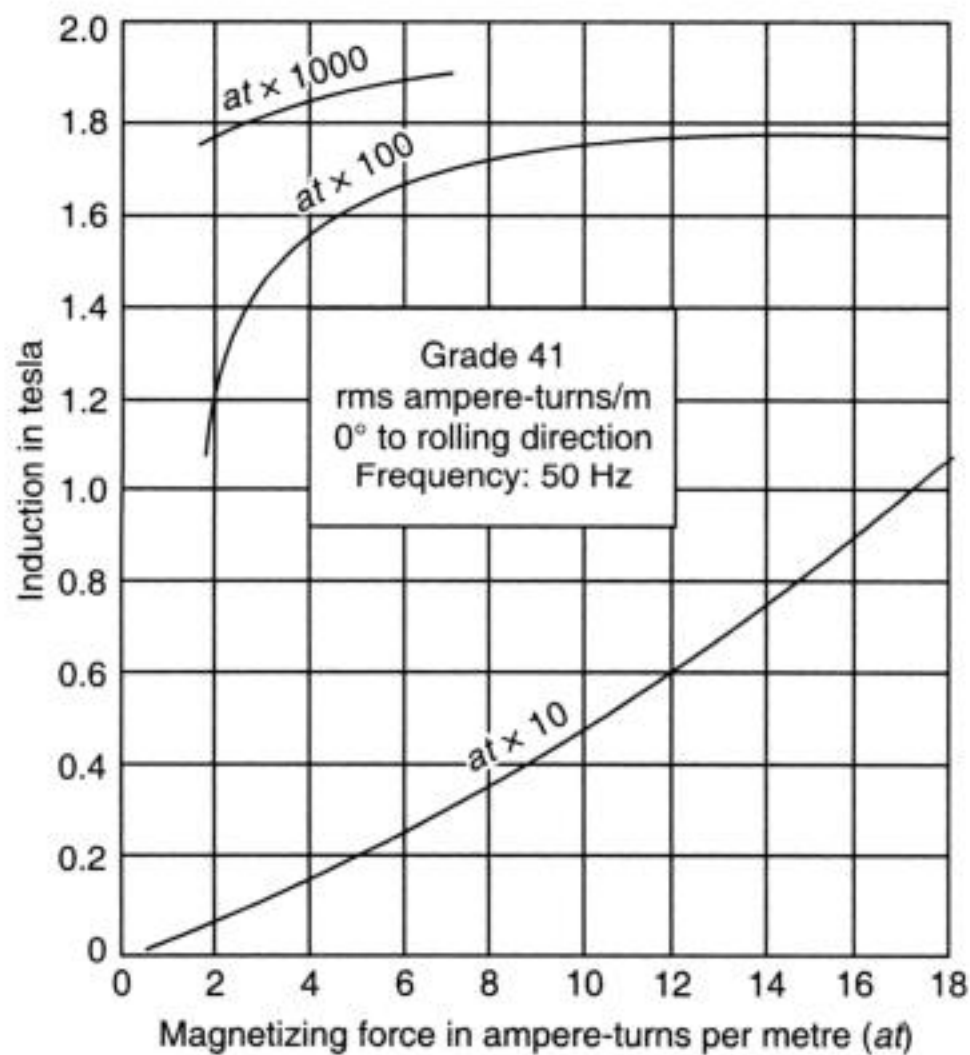


Figure 2.3(b) AC magnetization curve—peak induction density in tesla vs. magnetizing force in ampere-turns per metre (grade 41).

Figure 2.4 shows the ac magnetization curve of special Lohys.

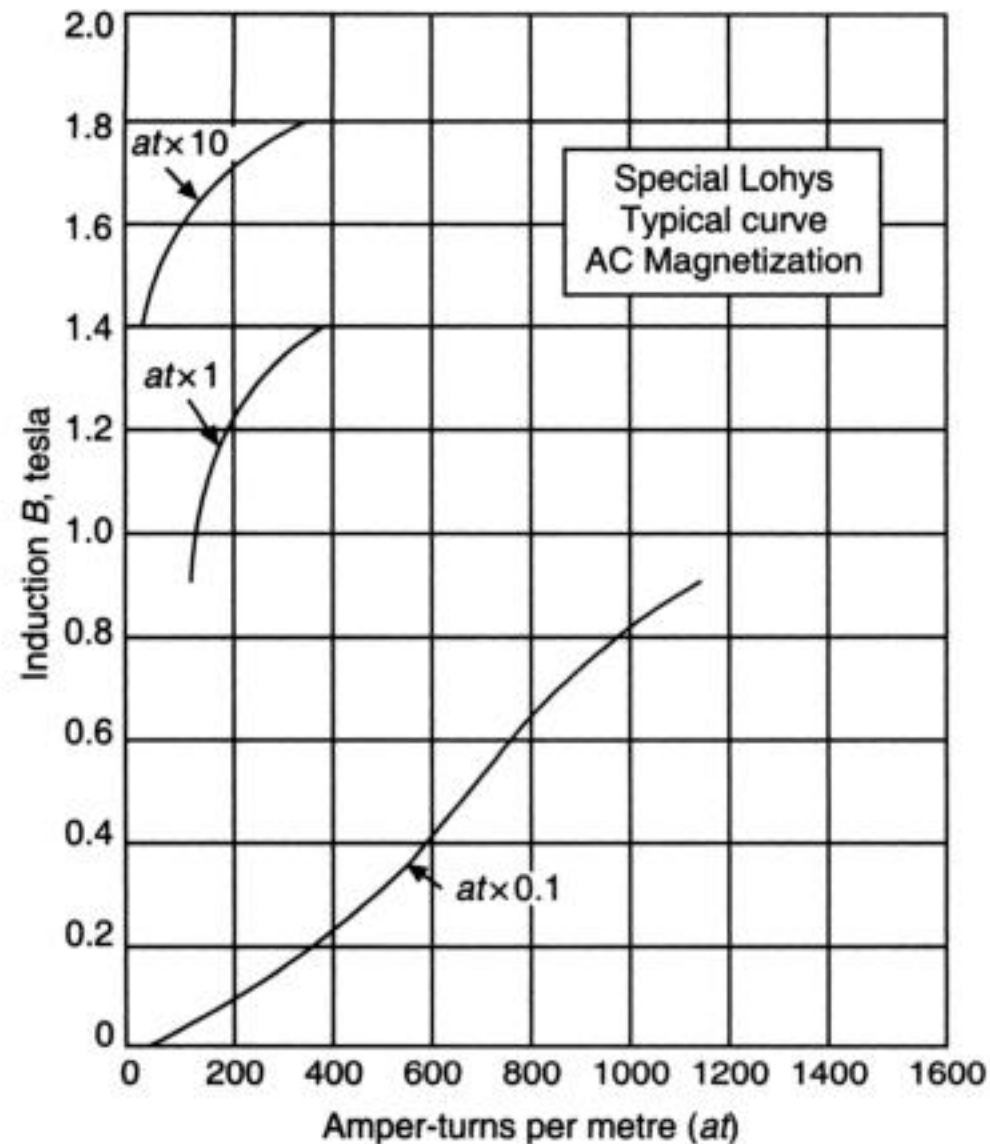


Figure 2.4 Induction in tesla vs. ampere-turns/m.

5. *DC magnetization curve:* This curve shows the normal magnetization characteristics of the grades in various thicknesses. The curve shows induction in tesla vs. ampere-turns per metre. Figure 2.5 shows such a curve for special Lohys and Figure 2.6 shows the curve for grade 51 sheet steel.

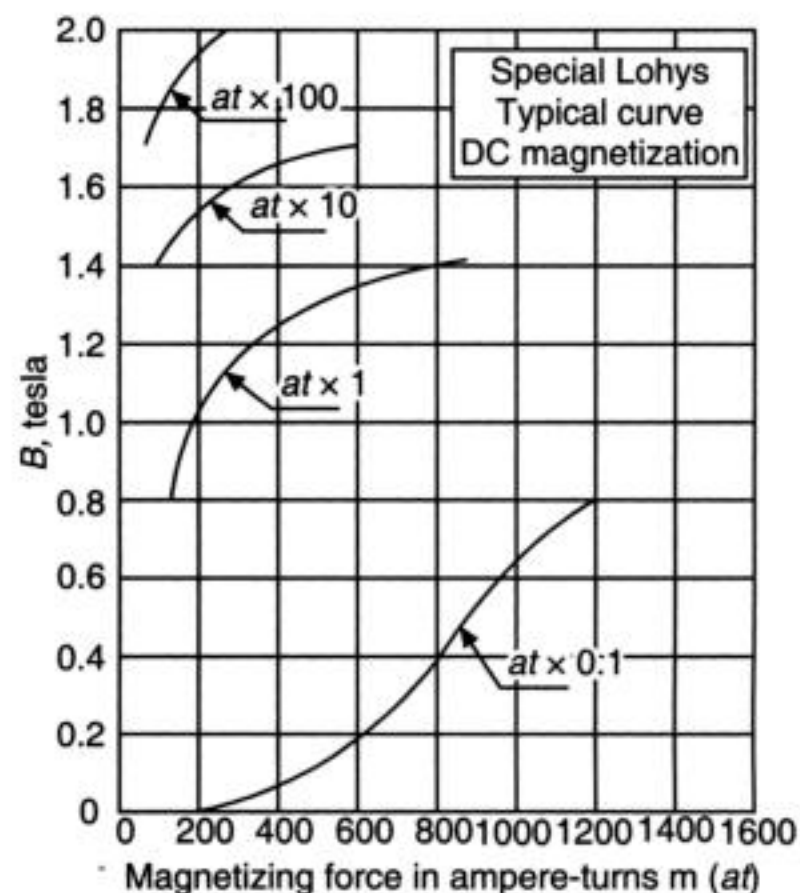


Figure 2.5 DC magnetization curve—induction in tesla vs. in ampere-turns per metre for special Lohys (0.5 mm thick).

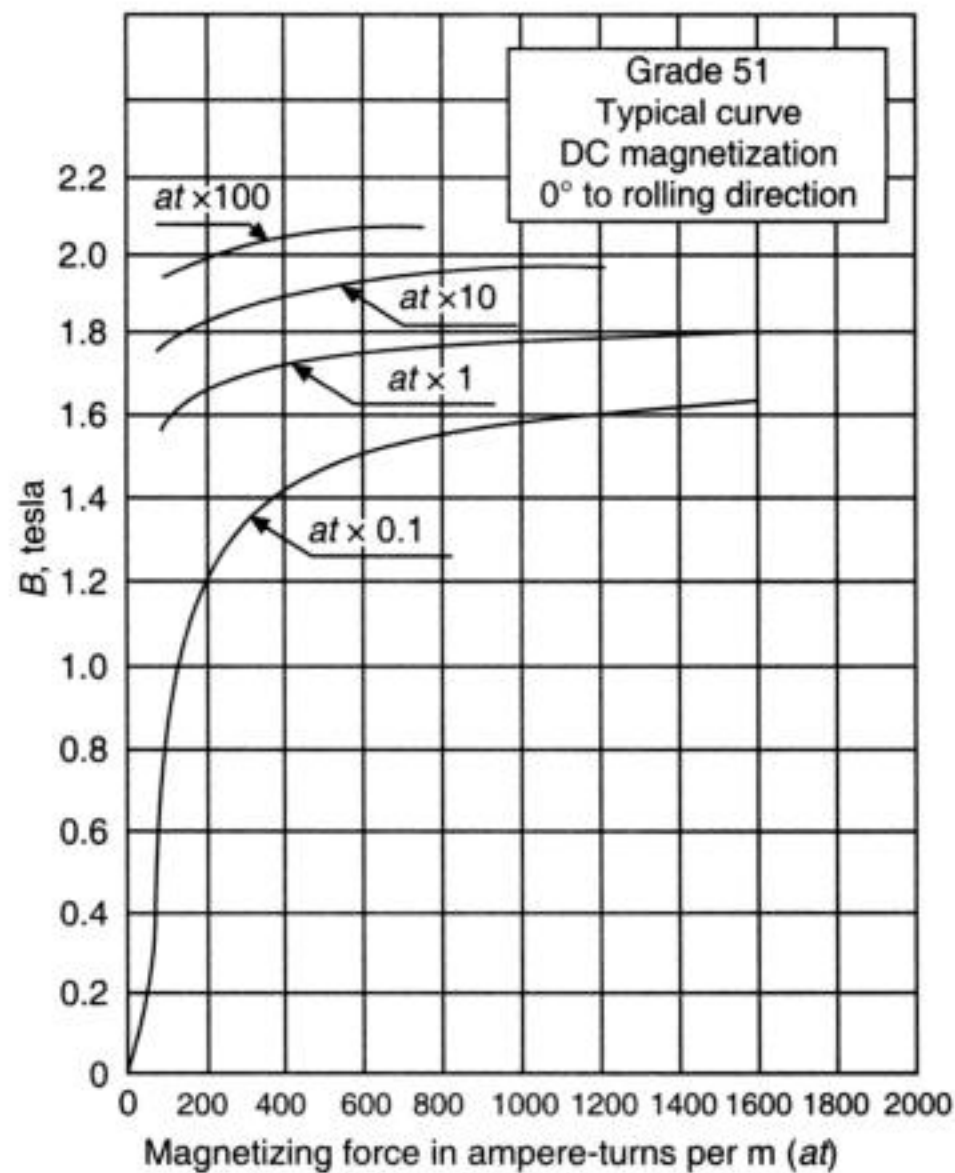


Figure 2.6 DC magnetization curve—induction in tesla vs. ampere-turns per metre for grade 51 sheet steel stampings.

2.3 TESTING OF MAGNETIC MATERIALS

The characteristics of magnetic materials such as those mentioned in the last section can be obtained by testing the material. Samples for core loss tests are tested in the Epstein Square Apparatus. The sheet material under test is arranged in thin sheets (0.35 mm) in strings of about 3 cm width and 50 cm length in four bundles to form a magnetic square. The ends are overlapped and kept pressed together or they are connected by corners of the same material. These bundles of the samples material are placed inside four rectangular coils connected in series through which current is passed. The circuit diagram with connections for the test is shown in Figure 2.7.

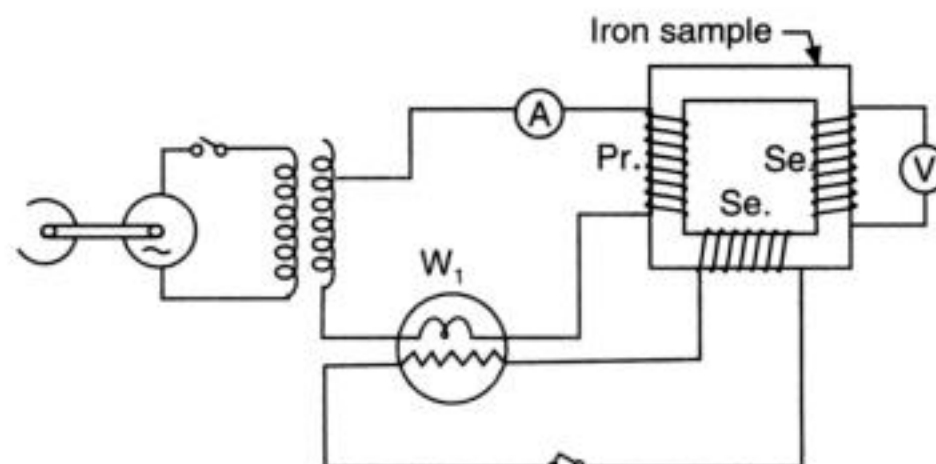


Figure 2.7 Iron loss measurement by Epstein's square.

There are three coils or windings in this circuit. One is the primary winding and the other two are secondary windings having the same number of turns as the primary winding. A voltmeter is connected across one of the secondary windings and the pressure coil of the wattmeter is connected across the secondary winding. The supply is given from a sine wave generator of special design. The ammeter A reads the no-load current which practically corresponds to iron loss current. Wattmeter W_1 reads the iron loss. The voltmeter V measures the voltage and the pressure coil of the wattmeter is supplied separately by another secondary winding giving the same voltage.

The secondary inductions were indicated by a flux voltmeter to assure sine wave conditions. The use of an rms voltmeter would give lower core loss values than those obtained with a flux voltmeter. These differences would be of greater magnitude at higher densities.

In building the magnetic square, half the strips in each sample were cut parallel to the rolling direction and half were cut perpendicular to that direction. These samples are not strain relief annealed.

In case of grain oriented grades, the tests are done on an Epstein's square of $3 \times 25 \text{ cm}^2$ strips sheared so that the flux path during testing is parallel to the rolling direction. These samples are strain relief annealed before testing.

The voltage induced read by the voltmeter is given in the Epstein's square just as in the case of a transformer—here the ratio is 1:1. The voltage $E = 4.44 \phi f T$ volts.

$$E = 4.44 B_{\max} A_c f T \quad (2.1)$$

where $B_{\max}$ = maximum induction in the core in Wb/m^2 or tesla

f = frequency of supply in Hz

T = number of turns on the primary or secondary

A_c = cross-sectional area of the core in m^2 .

Knowing the quantities A_c , f , T and reading E , the value of the flux density in the core of the square is calculated and the iron loss at this value of $B_{\max}$ is obtained by the wattmeter reading. Knowing A_c , the length of the strips, the weight of the sample under test can be found out or the sample strips weighed. The weight generally used for sample is 5 kg or 2 kg (for smaller square). The iron loss can then be determined in terms of watts per kg weight of the material for the required flux density. The values of the various flux densities are adjusted by varying the voltage applied to the primary winding and the iron loss for various values of $B_{\max}$ is read from the wattmeter readings.

1. *Core loss vs. frequency curve:* The frequency of supply from the sine wave generator is adjusted by the speed of the driving motor. Readings of the wattmeter are taken to determine loss at various frequencies for various magnitudes of induction.
2. *Volt-ampere vs. induction curve:* This is also obtained from the same experimental set-up. Volt-amperes (VA) per kg are obtained by calculations for the various flux densities at various frequencies as required. The current is read on an rms ammeter.
3. *Apparent ac magnetization curve:* The data for this curve is calculated from the volt-ampere curve data. Knowing the weight of the sample, and reading voltage and current, VA per kg can be obtained.

$$EI = 4.44 B_{\max} A_c f T I \text{ volt-amperes}$$

$$\text{VA per kg} = \frac{EI}{A_c L \times 7.75} = \frac{4.44}{7.75} B_{\max} \frac{f}{L} (at \times l_m) \quad (2.2)$$

where L = length of the strip in m, 7.75 = density of steel sample,
 at = ampere-turns per metre; l_m = length of winding in m.

$$\text{VA per kg} = 4.44 B_{\max} f l_m \times at$$

Thus for given values of $B_{\max}$ and f , and VA/kg, ampere-turns per metre can be determined. The curve of ac magnetization shows the plot of peak induction density in (tesla) vs. ampere-turns per metre (at).

4. *DC magnetization curve:* This is determined by direct current test by Fahy permeameter. The plot is for various values of flux densities in the sample on dc magnetization vs. ampere-turns per metre.
5. *Hysteresis loop:* Hysteresis loops for particular thicknesses and various gauges can be obtained and plotted. This curve shows variation of induction B in tesla vs. variation of ampere-turns per m. The sample is tested in a Fahy permeameter.

Hysteresis loops are of particular interest in designing cores of relays, magnetic switchgear and other specialised applications.

2.3.1 Separation of Iron Loss into Hysteresis Loss and Eddy Current Loss

The iron loss in a core consists of hysteresis loss and eddy current loss. They can be segregated for a certain flux density and at a given frequency as follows:

$$\text{Hysteresis loss} \quad W_h = k_h f B_{\max}^{1.7}$$

$$\text{and Eddy current loss} \quad W_e = k_e f^2 B_{\max}^2$$

where k_h and k_e are constants. If $B_{\max}$ is kept constant in the magnetic material during the test, then the total iron loss

$$W_i = W_h + W_e = af + bf^2 \quad (2.3)$$

where a and b are constants.

$$W_i/f = a + bf \quad (2.4)$$

A graph of W_i/f against f is plotted in Figure 2.8.

It is seen that this curve is a straight line with an intercept on the vertical axis equal to a , and the slope of this straight line is b . If a and b constants are determined for a certain flux density, the iron loss at that flux density can be separated into hysteresis and eddy current losses.

From Equation (2.1), it is seen that $E/f = 4.44 B_{\max} A_c T$. This is constant if $B_{\max}$ is maintained constant. Thus if E/f is maintained constant, $B_{\max}$ is constant.

Thus if variable frequency supply is given to the Epstein's square apparatus during a test and the ratio of voltage E read by the voltmeter and the frequency f of the alternator is maintained constant to the required ratio for a particular flux density at which losses are to be

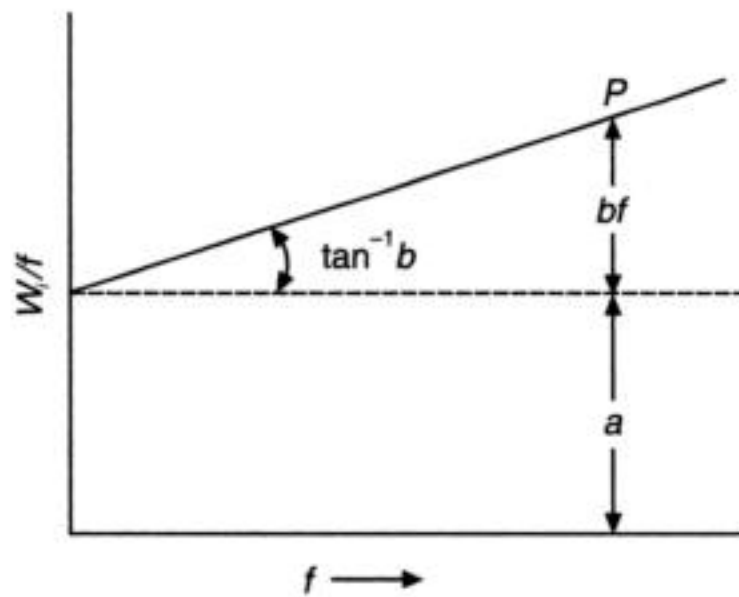


Figure 2.8 Separation of iron losses.

separated into hysteresis and eddy current losses if required. The value of the ratio E/f which is to be maintained constant during test can be calculated from Equation (2.1). The frequency of the alternator can be adjusted to the required value by adjusting the speed of the dc motor which drives the alternator.

EXAMPLE 2.1 The following are the test results obtained while testing a sample of sheet steel in an Epstein's Square Apparatus.

Terminal voltage, V	144	120	96	72
Frequency, Hz	60	50	40	30
Power input, W	20	15	11	7

- (a) Find the $B_{\max}$ to which the sample is subjected during the test if T = number of turns on the primary = 400 and the cross-section of the core of the sample $A_c = 9 \text{ cm}^2$.
Calculate the hysteresis and eddy current losses for frequencies of (b) 50 Hz and (c) 30 Hz.

Solution:

- (a) It is seen from the readings that $E/f = 144/60 = 2.4$. For other frequencies also the ratio $E/f = 120/50 = 96/40 = 72/30 = 2.4$. As this ratio is maintained constant during the test, the sample is being tested at constant $B_{\max}$. This value of $B_{\max}$ can be found out from the data given and substituting the values,

$$E/f = 4.44 B_{\max} A_c T$$

$$2.4 = 4.44 B_{\max} 9 \times 10^{-4} \times 400$$

or $B_{\max} = 1.5 \text{ Wb/m}^2 \text{ or } 1.5 \text{ tesla}$

- (b) As $B_{\max}$ is kept constant during the test,

$$W_i = W_h + W_e = af + bf^2$$

where a and b are constants. Substituting the values for 60 Hz and 50 Hz readings,

$$20 = a \times 60 + b \times 60^2 \quad (\text{i})$$

$$15 = a \times 50 + b \times 50^2 \quad (\text{ii})$$

Solving the equations (i) and (ii), $a = 0.133$; $b = 0.0033$

At 50 Hz, $W_h = a \times 50 = 0.133 \times 50 = 6.66 \text{ W}$

and $W_e = b \times 50^2 = 0.0033 \times 2500 = 8.34 \text{ W}$

Check: Total iron loss $W_i = W_h + W_e = 6.66 + 8.34 = 15 \text{ W}$

(c) At 30 Hz, $W_h = a \times 30 = 0.133 \times 30 = 4 \text{ W}$

and $W_e = b \times 30^2 = 0.0033 \times 900 = 3 \text{ W}$

Check: Total iron loss $W_i = W_h + W_e = 4 + 3 = 7 \text{ W}$

From the test, it is possible to separate out the losses at any intermediate frequency as well as find out the loss at that frequency approximately using the constants a and b . The constants may be found by choosing two equations near about the frequency at which the iron loss at the required frequency is to be found out or the values of a and b constants can be found out by plotting the curve of W_i/f vs. f as shown earlier.

EXAMPLE 2.2 From the readings of the test given in Example 2.1, and using the same constants a and b as calculated, find the total iron loss which will occur in the sample at $B_{\max} = 1.5$ tesla at 35 Hz. Separate out the hysteresis and eddy current losses at 35 Hz.

Solution:

From the last example $a = 0.133$; $b = 0.0033$. The hysteresis loss at 35 Hz for 1.5 tesla $= af = 0.133 \times 35 = 4.65 \text{ W}$. The eddy current loss $= bf^2 = 0.0033 \times 35^2 = 4.1 \text{ W}$.

The total iron loss $W_i = W_h + W_e = 4.65 + 4.1 = 8.75 \text{ W}$.

2.4 ELECTRICAL CONDUCTING MATERIALS AND THEIR CHARACTERISTICS

The main conducting material used in electrical machines is copper. Copper wires drawn to different gauges and insulated as required are used for windings of the machines. Aluminium is another conductor which is used in a limited way for the transformer windings when possible in smaller and medium sizes. This is because of the cost and availability considerations of copper. Aluminium is cheaper and abundantly available in India. Copper, however, has better characteristics than aluminium as far as its use as conductor is considered and is more commonly used in electrical machines. Copper conductor wires have different types of insulation coverings depending on the permissible temperature limits allowed in particular applications of machines, e.g. cotton covered, enamelled, paper covered, varnish bonded glass fibre covered copper conductors, etc. The conductors are round or rectangular in some applications. The Bureau of Indian Standards (BIS) have drawn up specifications for conductors so that they will be available in required sizes and characteristics.

The BIS specification on enamelled round winding wires stipulates that the copper conductor shall be of high conductivity annealed copper. The physical properties of annealed copper should be as follows:

1. Coefficient of linear expansion: 0.000017 per deg. C over a temperature range of 0 to 150°C.

2. Density: 8.89 g/cm² at 20°C.
3. The resistance of annealed copper conductor at 20°C shall be taken as 0.017241 ohm for 1 metre length and 1 sq. mm cross-section.
4. Temperature coefficient of resistance = 0.00393 per °C at 20°C. For any temperature $t^{\circ}\text{C}$,

$$\alpha_t = \frac{1}{234.45 + t}$$

The BIS specification gives details of the various copper and aluminium round conductors normally used. The sizes covered are for conductors of 0.020 mm diameter to 5 mm diameter. One conductor size is shown as illustration in Table 2.4A.

The data required for the various sizes of the conductors should be obtained from the latest standard and then used in the calculations for design purposes or for checking the test results.

The values of the permissible tolerance in diameters of the conductors, maximum and minimum resistance permissible for the various sizes and the values of the elongations at fracture for the various sizes of conductors are as per sample illustration in Table 2.4A. For small sizes of conductors, with diameter less than 0.071 mm, the diameter is checked by measurement of its resistance.

Aluminium conductors used are from 0.2 mm diameter to 5 mm diameter.

Aluminium: The material for aluminium conductor shall be electrolytic high conductivity annealed aluminium.

The physical properties of the aluminium conductors are as follows:

1. Coefficient of linear expansion: 23×10^{-6} per °C at 20°C.
2. Density: 2.703 g/cm³ at 20°C.
3. The resistance of annealed aluminium conductor 1 m long and 1 sq. mm in cross-section shall be 0.028 ohm at 20°C.
4. Temperature coefficient of resistance = 0.004 per °C at 20°C. For any temperature $t^{\circ}\text{C}$,

$$\alpha_t = \frac{1}{230 + t}$$

The diameters and resistances of the various aluminium conductors used are available from the latest BIS standards. One sample with diameter of 0.5 mm is given for copper as well as aluminium in Table 2.4A.

Table 2.4A Values of the permissible tolerance on diameters of the conductors, maximum and minimum resistance permissible for the various sizes and the values of the elongations at fracture for the various sizes of conductors

Nominal conductor diameter	Tolerance ± t	Resistance in ohms per m at 20°C							Elongation %	
		Copper			Aluminium					
		Nominal	Max	Min	Nominal	Max	Min	Copper min	Aluminium min	
mm	mm									
0.500	0.005	0.08781	0.09037	0.08534	0.1426	0.1476	0.1378	25	12	

The maximum and minimum values of resistivity of copper and aluminium are given below:

$$(i) \text{ Copper} \quad \rho_{\max} = \frac{1}{57.5} \Omega\text{-mm}^2/\text{m}$$

$$\rho_{\min} = \frac{1}{58.5} \Omega\text{-mm}^2/\text{m}$$

$$(ii) \text{ Aluminium} \quad \rho_{\max} = \frac{1}{35.2} \Omega\text{-mm}^2/\text{m}$$

$$\rho_{\min} = \frac{1}{36.2} \Omega\text{-mm}^2/\text{m}$$

- (b) The BIS specification for varnish bonded glass fibre covered copper conductors covers the requirements and methods of testing for single and double glass fibre covered copper conductors of sizes from 0.250 mm to 4.00 mm, the glass fibre being bonded with suitable highly polymerized thermosetting varnish of temperature index of at least 130°C.

The material specification, diameter, sizes, tolerances, resistance per metre at 20°C, are mentioned in the standard together with the properties of each size of conductor.

In addition to the normal tests for checking diameter, thickness, resistance, the bending test, and the elongation test, the conductor is subjected to breakdown test as well. This test is done at room temperature and at rated temperature for the use of the conductor.

Test for conductor sizes over 2.4 mm diameter

Five electrodes are prepared by applying a strip of thin metal foil having a width of 6.0 mm to the centre of a pressure sensitive tape 12.0 cm wide. A sample of wire of such length is used so that the five electrodes can be applied at intervals of approximately 50 mm. The glass covering is removed from one end of the sample and the voltage is applied between the conductor and each electrode in turn, thus giving 5 tests on the sample wire.

The test voltage is alternating and of 50 Hz. The test transformer should have at least 500 VA rating and current supplied be sinusoidal. The voltage is applied at zero and increased at a uniform rate of 100 V per second until breakdown occurs. If the breakdown occurs in less than 5 seconds, the rate of increase of voltage for the test is reduced, while if the breakdown voltage is equal to or greater than 2500 V, the rate of rise of voltage should be 500 V per second.

The BIS specification gives the minimum values of the breakdown voltages for various sizes of conductors, e.g. for 2.5 mm, 3.30 mm and 4.00 mm diameter conductors, the minimum breakdown voltage values (rms) at rated temperature for double covering are 540 V, 270 V and 340 V, respectively.

- (c) The BIS specification for rectangular conductors required for stators of large machines and transformers, gives the width and thickness of several sizes of rectangular conductors. The specifications gives the nominal cross-sectional areas for the preferred sizes of conductors.

Conductors whose width/thickness ratio is smaller than 1.4:1 and whose ratio of width/thickness is over 8:1 are not recommended. Widths from 2 mm to 16 mm and thickness from 0.8 to 5.6 mm are covered in this standard.



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enamel or fibre glass braided and varnished with polyurethane. For Class H insulation, polyamide-imide based enamel is used; Silicon resin based enamelled and fibre glass covered conductors are also used for Class H application.

- (b) *High voltage insulation:* In the beginning, the high voltage material was bitumen used with mica; these were thermoplastic material of Class B. With the development of epoxy novolac resins, bitumen is not used. For Class F insulation, mica folium and glass fabric enriched by epoxy resin are used. Most of the present day high voltage electrical machines use epoxy mica glass tapes of the resin rich or the resin poor type. If composite materials with polyamide filaments and mica are used, it is possible to obtain Class H insulation properties.
- (c) *Slot insulation:* For Class A and Class F insulation, slot insulation is made up of leatheroid material. For Class B insulation, the slot liner is made up of presspahn combined with polyester film. For Class F slot insulation, polyester mat with polyester film or flexible mica backed with varnished glass fabric or asbestos paper with nomax or polyester film with resin bonding is used. For Class H insulation, silicon based glass fabric is used. Flexible micanite with suitable resin or polyamide films are used for Class F and Class H insulation.
- (d) *Slot wedge:* For Class B insulation, bakelised fabric wedge is used. For Class F insulation, epoxy glass cloth laminate or Resin bonded asbestos paper laminate material is used. For Class H insulation, Silicone resin bonded glass fabric laminate or silicone resin bonded asbestos paper laminate is used as the material for slot wedges.
- (e) *Inter-turn insulation:* For Class B insulation, polyester enamel or varnished double glass or isophthalate varnish glass tape is used. For Class F insulation, esterimide enamel or polyurethane varnished double glass or polyester felt tape is used as insulation material.
- (f) *Coil-to-coil and phase-to-phase insulation:* Inside slots; Fibre glass backed mica is used as coil separator for Class B insulation. For Class F insulation, polyamide paper with polyester film backing is used as the coil separator.
- (g) *Winding overhangs as phase separator:* For Class B insulation, isophthalate varnished glass and wet varnished treated glass tape is used. For Class F insulation, the same material is used; also polyurethane glass fabric with polyester film or polyester non-woven mats can be used. For Class H insulation glass fabric with silicone elastomer coating is used.
- (h) *Phase-to-ground insulation:* Class B insulation used is fibre glass backed mica sheet while for Class F insulation polyamide paper with polyester film backing material is used.
- (i) *Banding tapes and cords:* For Class B insulation, fibre glass varnished tapes are used. For Class F insulation, polyurethane varnished glass fabric tape or cord; varnished polyester tape or chord are used. For Class H insulation, glass fabric tape or chord, with silicone elastomer cover is used as material.



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Table 2.9 Properties of fibre glass epoxy laminated sheet

Composition:	Epoxy resin 40% (by wt.) Fibre glass support 60% (by wt.)	
Density:	1.7 to 1.9 g/cm ³	
<i>Physical and Chemical Properties:</i>		
Water absorption: 4 mm 24 hours	23°C H ₂ O	0.15% (wt.)
Oil absorption: 4 mm 3 hours	130°C Oil	0.05% (wt.)
Resistance against solvents, mineral oils, acids, bases: good.		
Thermal properties; Class F: Max temperatures in services 155°C		
Short-time temperature 4 hours 165°C.		
<i>Mechanical Properties:</i>		
Tensile strength:	3000 kg/cm ²	
Compressive strength:	4000	
Bending strength:	4000/1500 at 20°/150°C	
Impact strength:	100 kg cm/cm ²	
<i>Electrical Properties:</i>		
1 min test voltage 3 mm	140 kV/cm	
Electrical strength:	150 kV/cm	
Surface resistivity:	10 ¹² Ω-cm	
Insulation resistance:	10 ¹² Ω-cm	
Volume resistivity:	10 ¹² Ω-cm	
Power factor: (tan δ) 1 MHz	0.02	
Dielectric constant: at 1 MHz	4.8	

Table 2.10 Some properties of insulating varnishes of Class B

Solid content 49.51%; Density 0.9 g/cm ³
Flash point 35°C; Viscosity 60–75; Storage stability 12 months
Dielectric strength 60 kV/mm; Volume resistivity 10 ¹⁵ Ω-cm;
Water absorption 3 mg in 96 hours at room temperature
Base: Oil modified phenolic
Excellent flexibility, good bonding and dielectric properties, resistant to acid, alkalies, transformer oils and tropical conditions
<i>Applications:</i> Impregnation of wide range of electrical machines, transformers, enamelled wires and explosion proof equipment

Table 2.11 Some properties of insulating varnishes Class F

Solid content 49–51%; Density 0.96 g/cm ³
Viscosity 65–85; Flashpoint 29°C; Storage stability 12 months
Base: Isophthalic alkyd
Dielectric strength at room temperature : 65 kV/mm; at 155°C 55 kV/mm
Volume resistivity 10 ¹⁶ Ω-cm
Water absorption 7.5 mg in 96 hrs at room temperature
<i>Applications:</i> Impregnation of electrical equipment including explosion proof large machines requiring increased flexibility

Table 2.12 Some properties of insulating varnishes Class H

Base: Modified esterimid

Solid content 47–49%; Density 1.07 g/cm³; Viscosity 75–85;

Flashpoint 38°C; Storage stability 12 months

Dielectric strength at room temperature 70 kV/mm

Volume resistivity 10¹⁶ Ω-cm

Water absorption 6.5 mg in 96 hrs at room temperature

Applications: Impregnation of traction motors, high voltage machines and large size turbo alternator coils

Table 2.13 Some properties of impregnating resins of Class B

Resin base and type: Unsaturated polyester transparent liquid.

Viscosity 350 = 450; Gelling time 20–30 minutes at 100°C;

Curing time 6 hours at 120°C; 2 hours at 140°C;

Dielectric strength 70 kV/mm at R.T.; 60 kV/mm at 130°C

Specific resistance at R.T. 10¹⁵ Ω-cm; at 130°C 10¹⁴ Ω-cm

Applications: Impregnation of standard motors up to frame 355, large size special rotating machines, instrument and small transformers

Table 2.14 Some properties of impregnating resins of Class F

Resin base and type: Unsaturated polyesterimide transparent liquid.

Viscosity 450–550; Gelling time 20–30 minutes at 100°C;

Curing time 4 hours at 120°C; 1 hour at 140°C

Dielectric strength 90 kV/mm at R.T.; 80 kV/mm at 155°C

Specific resistance 10¹⁵ Ω-cm at R.T.; 10¹² Ω-cm at 155°C

Applications: Impregnation of normal and special motors up to 355 frame size; H.T. motors and D.C. machines

2.9 USE OF CLASS F AND CLASS H INSULATIONS IN THE DESIGN OF ELECTRIC MOTORS

At present, Class F and Class H motors are made for specific applications only, e.g. (i) where ambient temperature is high; (ii) Location of mounting of motors does not permit cooling facilities; (iii) Limitations of space require smaller frame size for motors; (iv) Duty cycle for motors such as plugging, reversing, frequent starting; (v) Slip ring rotors.

The design approach in using Class F and Class H insulations may be of two kinds:

- (a) If a standard motor is required to work at a higher ambient temperature or without fan cooling, it will be necessary to use a higher frame size or derating of the motor. Higher size will mean the use of more active materials such as copper and iron in the motor. Instead of doing this the designer can use a higher class of insulation such as Class F

and Class H as needed without going in for larger size of frame and use of more active materials in the motor.

- (b) The designer can use higher thermal characteristics of Class F and Class H insulations to design the standard range of motors to reduce the frame size, reduce the use of active materials in the motor, and thus reduce the cost. The disadvantage is however that the performance of the motor deteriorates, e.g. the power factor, efficiency, starting torque, and speed are lower than with the use of normal size and class of insulation. The running costs of the motor are higher and the motor runs hotter. An approximate comparison of the performance of the motor and the active materials used in its construction of Class B and Class F motors is shown in Table 2.15.

Table 2.15 Compare Class B and Class F insulated motors (low voltage)
active materials used and the performance

Active materials	Class B	Class F
Winding copper wire	100%	65 to 75%
Laminations steel	100%	90 to 92%
<i>Performance:</i> With Class F insulation, compared to Class B insulation, no load current is 3 to 5% more, efficiency is 4 to 6% less, power factor is 2 to 3% less, starting torque is 40 to 45% less and speed is less by about 10 to 15 rpm		

2.9.1 Relative Study for Using Insulation of Higher Class

The effect of thermal conductivity of insulation with respect to kW output of the machine can be seen by the relation

$$\Delta T = \frac{Qd}{AK} \quad (2.7)$$

where ΔT = temperature difference between the opposite faces of slot insulation

A = surface area; $Q = I^2R$ loss

K = thermal conductivity

d = insulation thickness.

For full utilisation of Class F and Class H insulations, let the outputs of the machine be increased by αF and αH over the outputs with Class B insulation of the motor.

Assuming that the power factor and the efficiency remain fairly constant, full load current proportionately varies with αF and αH respectively.

Then
$$(I^2R)_F = \frac{235 + 140}{235 + 120} \alpha F^2 \times (I^2R)_B, \text{ i.e. } 1.056 \alpha F^2 (I^2R)_B \quad (2.8)$$

and
$$(I^2R)_H = \frac{235 + 180}{235 + 120} \alpha H^2 \times (I^2R)_B, \text{ i.e. } 1.169 \alpha H^2 (I^2R)_B \quad (2.9)$$

Assuming the same effective insulation thickness,



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Construction of Electrical Machines

3.1 CLASSIFICATION OF ELECTRICAL MACHINES BY CONSTRUCTIONAL FEATURES

The tentative classification of electrical machines by constructional features and their subdivision into power output ranges and speed ranges can be done. This is considering typical common constructional features for the ranges of machines considered. With reference to power outputs the machines may be classified as:

- (a) Small electrical machines with an output of up to 0.6 kW.
- (b) Medium size electrical machines with power outputs up to 250 kW.
- (c) Large size electrical machines with output higher than 250 kW to about 5000 kW.

These machines are manufactured in a series of standard power ranges required.

Another way to classify electrical machines is by their speed. This classification may be as follows:

- (d) Low speed machines 250–400 rpm.
- (e) Medium speed machines 400–1500 rpm.
- (f) High speed machines with a speed of more than 3000 rpm.

3.1.1 Mechanical Construction Features of Electrical Machines

The typical mechanical construction features of electrical machines are forms of horizontal shaft machines, forms of vertical shaft machines, along with the types of ventilation and cooling used for the machines, types of enclosures and types of frames.



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Frames

The stator core of an electrical machine is assembled in a suitable figure. The frame in medium size machines and small machines are of a hollow cylindrical shape; large size machines have frames of the shape of a circular box. The frame is provided with feet and the machine is fixed to the bed plate by these feet. The size of the frame of a machine is given by the distance of the centre of the shaft of the rotor from the base.

Stator windings

Stator winding is a set of conductors wound in the form of coils, placed in slots and connected in a suitable way to obtain required voltage in case of generator action and to work on required applied voltage in the case of motor action. Most common machines will be three-phase machines; the windings commonly used will be double layer windings and sometimes single layer windings. All coils of double layer winding are identical. Single layer windings may be divided into two types. Simple concentric windings: These are used for single-phase motors. The other type commonly used for three-phase machines also is chain or mush winding. In this case, the coils of the winding are not identical coils. The overhang of each coil overlaps the overhangs of all the coils lying between its coil sides.

When the machine has open slots, the winding coils are placed in slots wound in suitable way. The coils are generally multiturn coils. Wedges of bakelite or wound are used to fix the winding in the slots. In case of semi-closed slots, one conductor of the coil-wire is inserted in slot opening at a time. Typical arrangements of conductors in a slot are shown in Figure 3.6.

The end connections are properly insulated. The end connections are properly fixed to withstand the mechanical forces which may be produced when the machine is short-circuited under fault condition.

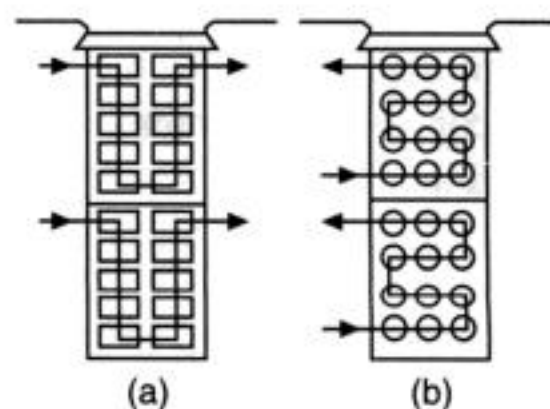


Figure 3.6 Typical arrangements of conductors in a slot.

3.3 CONSTRUCTION OF ROTORS OF AC MACHINES

The slip ring type of induction machines have wound rotor construction; the squirrel cage induction motor on the other hand has bars with short-circuit at the end rings. In case of synchronous machines, the rotor has field poles and dc excitation. The construction has to be seen separately for these machines with the particular arrangements.

3.3.1 Wound Rotor Induction Motors

The core construction is similar to that of the stator core, namely use of laminated sheet, steel punchings, a suitable number of slots and three-phase or sometimes two-phase winding on the rotor. The diameter at the air-gap is worked out and the depth of rotor core is found out allowing for the necessary flux density in the rotor core. The core is fixed on the shaft or the rotor spider. The types of the slots used are semi-closed slots with tapered teeth. A typical type of semi-closed slot arrangement on the rotor is shown in Figure 3.7.

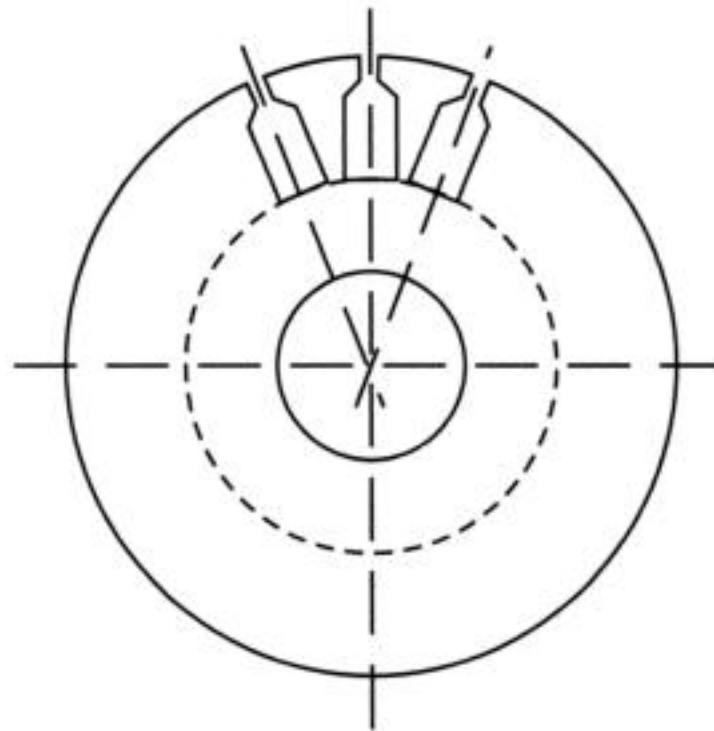


Figure 3.7 Rotor slots arrangement: Semi-closed slots with tapered teeth.

The rotor winding is a bar winding with connections of half coils from outside. Bar wave windings are commonly used. Sometimes single layer windings are used for the rotor of induction motors. These are usually concentric coils three-phase windings having two plane end windings. In some machines, three-phase double layer windings can also be used.

3.3.2 Squirrel Cage Induction Motors

The standard purpose induction motors will generally be of squirrel cage rotor construction. The core is made of sheet steel laminations as those of stator laminations. As the frequency of the voltage induced is that of slip frequency which is small compared to the main supply frequency of the stator, the thickness of the rotor punchings may be larger than that of the stator core punchings as the iron losses will be low. The rotor core is generally fixed on the shaft and properly keyed. The winding is by means of copper bars with end rings connected from the ends. In general aluminium die cast rotors are commonly used for motors of small and medium size squirrel cage motors. The rotor conductors and end rings are die cast together.

3.3.3 Rotors of Synchronous Machines

Synchronous machine rotors with low power outputs will have salient poles on the rotor. The field winding is wound on the poles to which DC excitation is supplied through the slip rings.

The salient poles are solid poles with laminated pole shoes. The poles of modern synchronous machines which have damper windings are made up of sheet steel laminations. The thickness of laminations is 1 to 1.5 mm. The poles have end steel plates on both the sides. Rivets or counter sunk bolts are used to fix these laminations together. Dovetails are used to fix the poles on the rotor spider or the rotor wheel rim. Figure 3.8 shows a solid pole with a laminated pole shoe arrangement and space for field winding.

Figure 3.9 shows the arrangement of the salient pole and the field winding; the laminated pole being fixed to the rotor body by dovetails. The laminated sheet steel punchings forming the pole are bolted together using thicker end plates on either side.

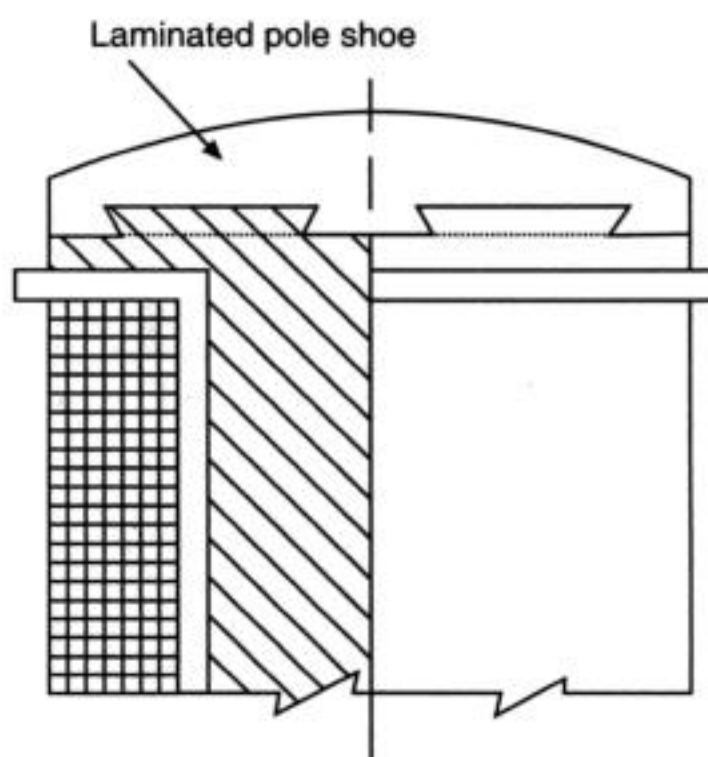


Figure 3.8 A solid pole with a laminated pole shoe arrangement for a salient pole of synchronous machine.

Figure 3.10 shows the arrangement of fixing the laminated pole to the spider of the rotor. The pole also has damper winding slots.

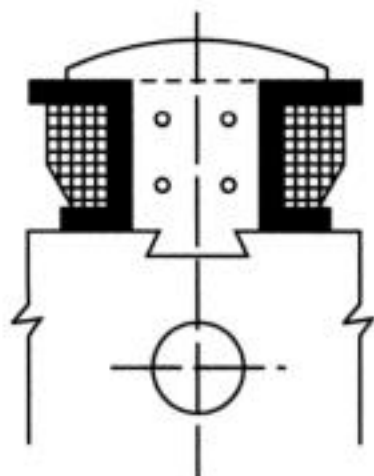


Figure 3.9 Salient pole—laminated and with dovetails.

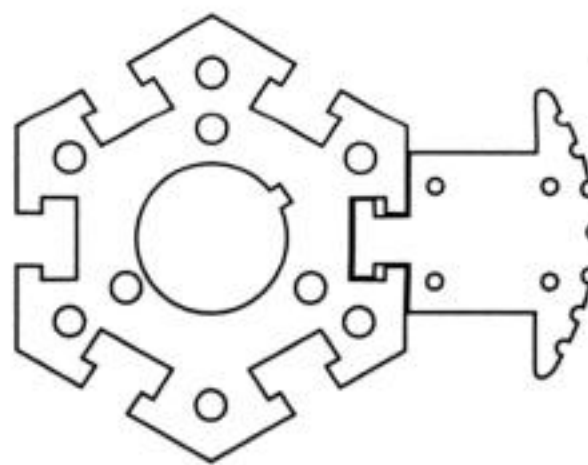


Figure 3.10 Spider and pole punchings.

The various other arrangements used for fixing the poles to the rotor body are pressed in dovetails, tapered dovetails, and single or multiple T heads.

Field coils of rotor poles are usually of round copper wire with double cotton or double fiberglass insulation. The coil has multi-turns and a large number of layers. Generally, the field coil is wound on a framework made up of sheet steel and insulated from the winding by presspahn of 0.2 to 0.3 mm thickness. The coils are impregnated with baking varnish and then baked. The arrangement for the framework of the field winding is shown in Figure 3.11.

Non-salient pole construction is used for large turboalternators. In such cases, the field winding is made up of copper strip wound on narrow edge and placed in rotor slots. Mica 0.10 to 0.20 mm thick is used as insulation between turns. All field coils are insulated in the rotor slots by micanite 1.2 to 2.0 mm thick.

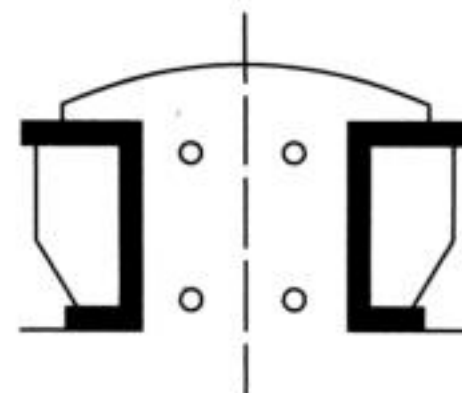


Figure 3.11 Framework for field coil winding.



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slots, with necessary slot insulation and coil insulation. Wedges are used at the end of each slot mouth to ensure that the coils are held firmly. The coils are held in place by steel band wires wound on the core of the armature at two or three places in the notches provided in the core.

The armature winding may be simple lap or wave winding. In larger machines, multiplex windings are used. The connections from the coils of the winding are brought to the other side to the commutator and connected to segments of the commutator as per the type of winding used.

3.5 CONSTRUCTION OF COMMUTATORS AND SLIP RINGS

Slip rings for synchronous machines

Slip rings are used for synchronous machine rotors to give connections to the field winding. In small size synchronous machines, slip rings are placed on the shaft between the bearing and the rotor core. In large turbo alternators, slip rings are located on the shaft outside the bearing. Rings are made of steel and while hot are placed on a cast iron sleeve press fitted by micanite. The assembly of sleeves with two slip rings is placed on the rotor shaft and keyed to it. Figure 3.17 shows the arrangement of slip rings for small synchronous machines.

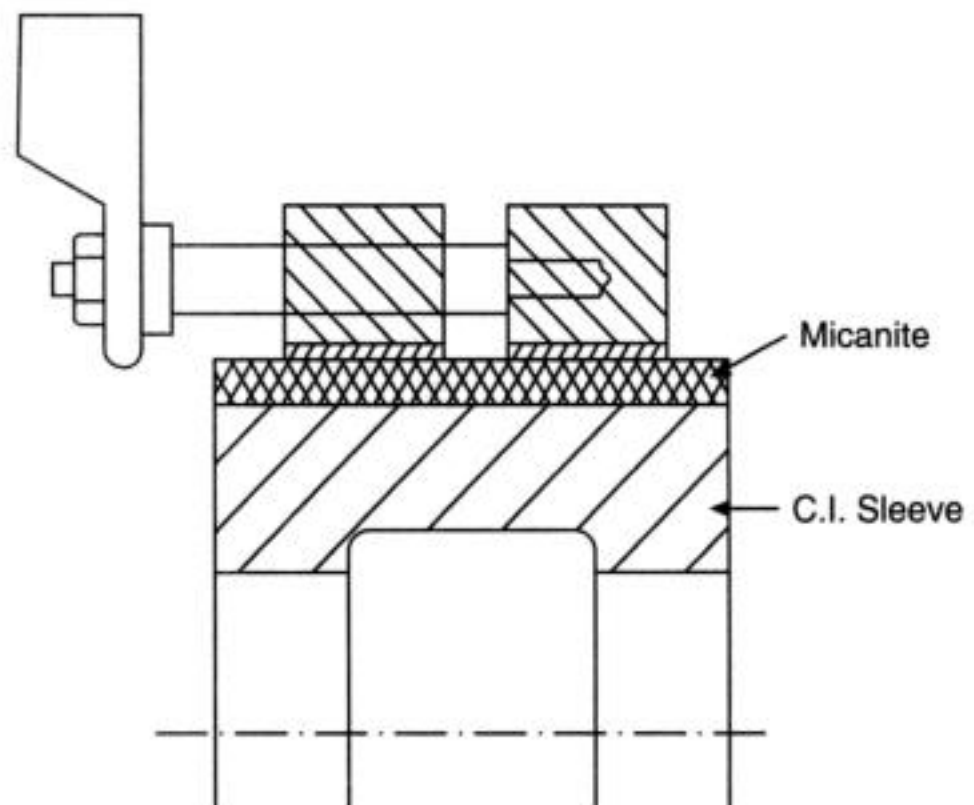


Figure 3.17 Slip rings for a small synchronous machine.

In the case of large synchronous machines, slip rings are made as castings and then they are fixed to the flange of their sleeve.

Slip rings for induction machines

For the wound rotor induction motor, three slips would be necessary on the rotor. Slip rings for small induction motors are made of bronze or steel and while hot are shrunk on a cast iron sleeve insulated by flexible micanite of about 2.0 mm thickness. These rings are separated by insulating rings made of plastic with asbestos. Figure 3.18 shows such a typical arrangement.

Large induction motors have their rotor windings shorted after starting and have a device for short-circuiting the slip rings and lift of the brushes.

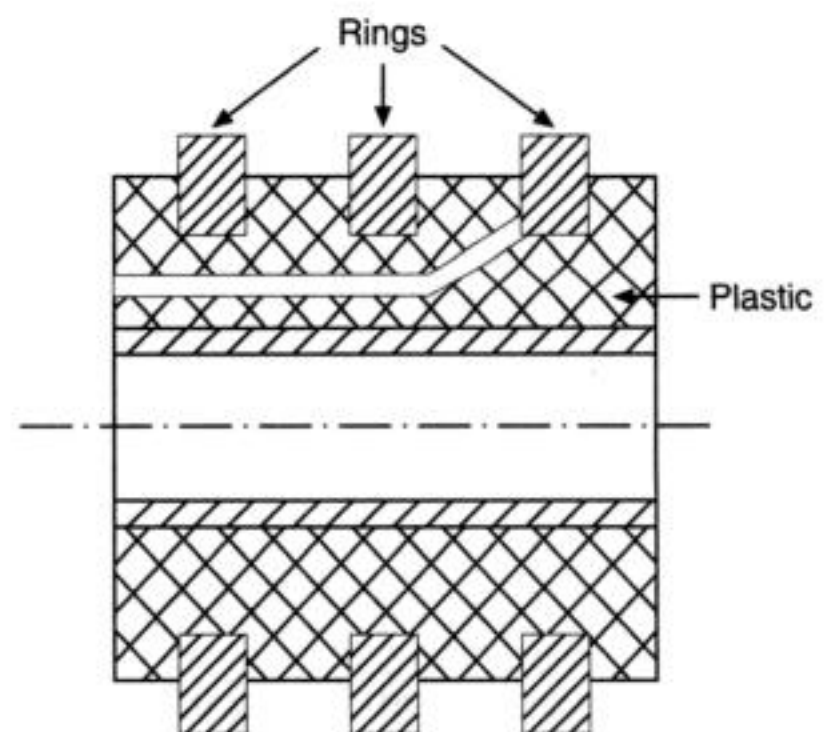


Figure 3.18 Slip ring construction for a small induction motor.

Commutators

There are two types of constructions used for commutators.

- (a) Cylindrical commutators in which bars are fastened by conic clamping rings. This is the common type of construction.
- (b) Cylindrical commutators in which bars are braced by shrink rings. This type of construction is used for high speed machines. Figure 3.19 shows a section through the commutator of a dc machine. The commutator hub is provided with a fixed flange at one end. Between this flange and the end ring the commutator segments are arranged as shown. The segments have V grooves and insulation in the grooves in micanite rings. The segments have risers and the leads of the armature are soldered to risers to effect connections. Brushes are located on the commutator in a neutral axis.

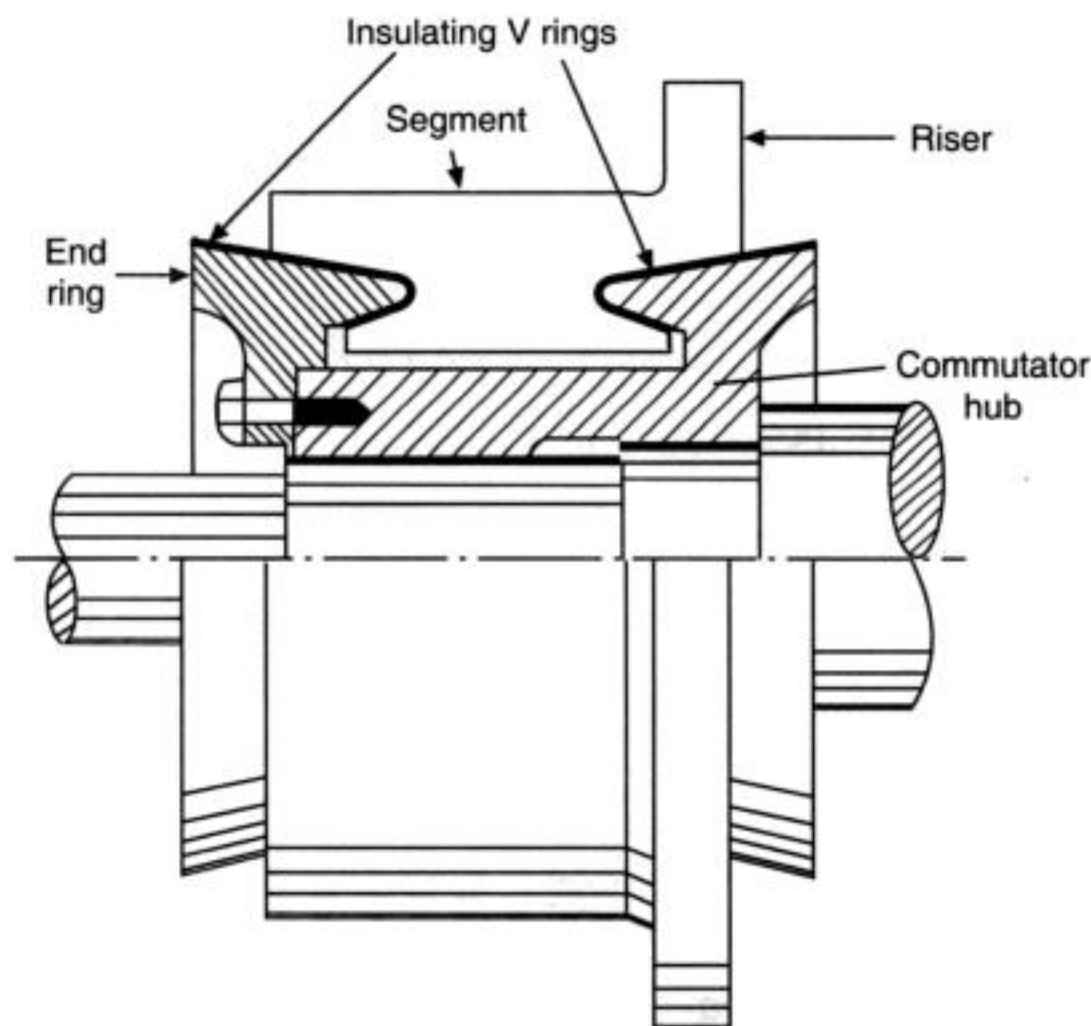


Figure 3.19 Section through a commutator of a dc machine.

In the case of medium size of commutators with diameters between 140 mm to 1000 mm, it is necessary to have passage of cooling air through armature and the commutator. Figure 3.20 shows a typical construction of this type of commutator.

The ducts for cooling are provided between the sleeve of the commutator and the shaft.

3.6 BRUSHES AND BRUSH HOLDERS

The brush material used for the manufacture of brushes is one of the following:

- (i) Hard carbon; (ii) Carbon graphite; (iii) Natural graphite; (iv) Electrographite; (v) Metal impregnated graphite; and (vi) Resin bonded.

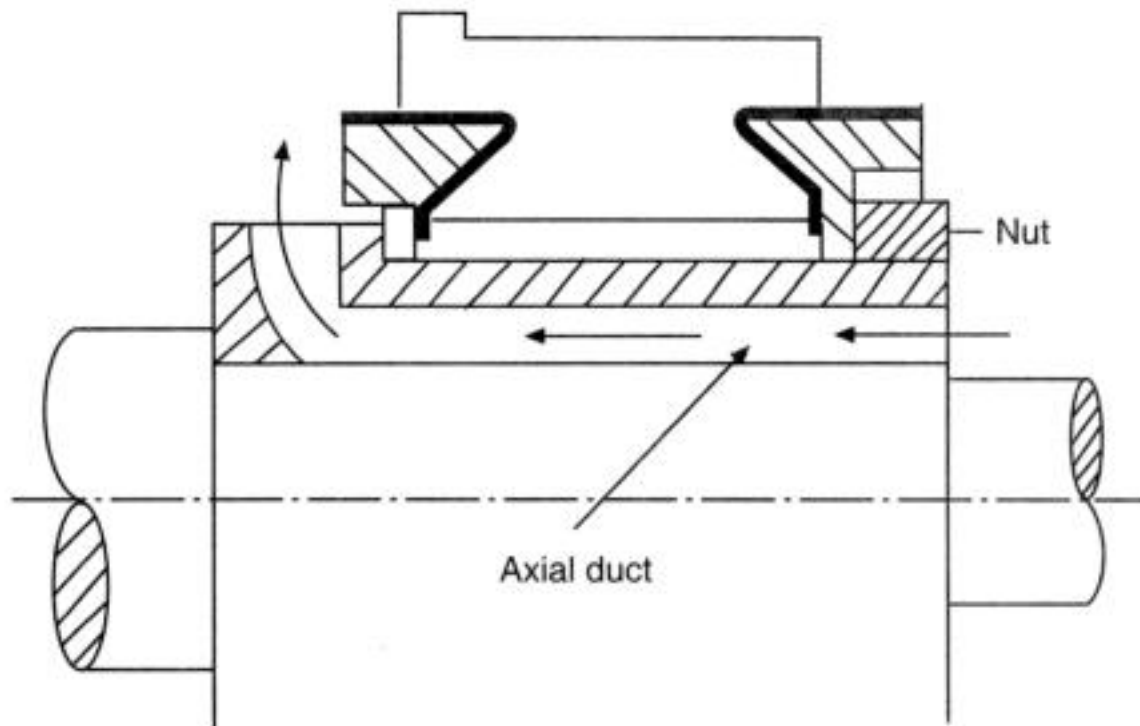


Figure 3.20 Commutator for a medium size dc machine.

Metal graphite brushes are mainly used in induction and synchronous machines while in the case of dc machines normally carbon graphite and electrographite brushes are used.

Indian standard specification IS:3003 (Part III) 1972 gives specifications for carbon brushes used for electrical machines.

For reversible machines, the brush holders set the brushes in radial position, while for machines which have one direction of rotation and are not reversible, the brush holders set the brushes in an inclined position. The brush holders should provide the required pressure on the brush, and distribute the pressure uniformly for good contact of the brush with the slip rings or commutator segments. The movement of the brushes in the brush holder box should be free and it should be easily accessible for substitution of brushes when they need change or inspection. Spring pressure on brushes should remain constant within limits permissible for brush wear. Brush holders may be single brush or double brush holders.

In the case of small synchronous machines and induction motors of medium size, the connection between the brush and the brush holder is affected by means of a screw. For dc machines and large size machines, the electrical connection of the brush with current carrying terminal of the brush holder is made by a flexible lead of copper wire called a pig tail. This is fixed to the brush.

3.7 CLASSIFICATION OF ELECTRICAL MACHINES BY MECHANICAL CONSTRUCTION FEATURES

Electrical machines may be classified based upon the following features of mechanical construction.

- (a) *Electrical machines with two end shield bearings:* This is a common type of construction for electrical machines. Power output of such machines may be hundreds of kW. The outside frame sizes are up to 1200 mm maximum. This type of machine can be mounted horizontally on the floor, or on the wall. The machines of this type are foot-mounted. The machines of this type may also be flange mounted. Figure 3.21 shows a foot-mounted machine.

- (b) *Electrical machines with pedestal bearings:* Machines with two pedestal bearings are mounted on a common bed plate for coupling with other units. Machines with additional pedestal bearing type construction are used for belt drive or rope drive. Machines with single pedestal bearing type construction use a flange for coupling these machines with the other machines. This type of single pedestal bearing type of construction is sometimes used for machines with a large air-gap such as synchronous machines or dc machines.

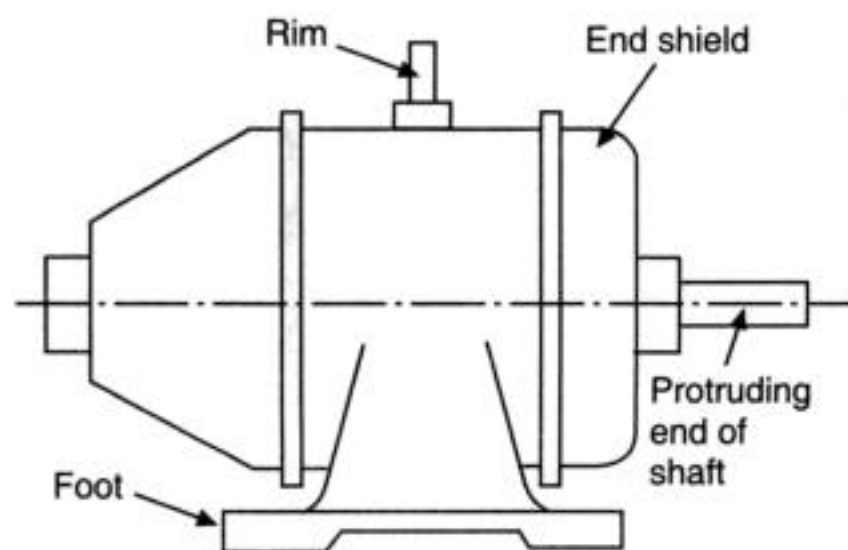


Figure 3.21 Foot-mounted electrical machine.

- (c) Vertical shaft construction is generally used for low speed hydro-electric generators. *Suspended type* machines have thrust bearing above the rotor and two guide bearings—upper and lower.
- (d) *Umbrella type construction:* Electrical machines of this type of construction have thrust bearing below the rotor.

3.7.1 Classification of Machines by the Method of Protection

Electrical machines need protection from the surrounding medium such as dust, dampness, active gases, tropical conditions, high ambient temperature near the location of installation, etc. Depending on the type of mechanical protection provided for the machines, they are classified into the following types:

- (a) *Open type of machine:* They do not have any special type of protection.
- (b) *Hose proof or water tight machines:* These are constructed in such a way that water applied in the form of a hose stream will not enter the machine so as to effect its operation.
- (c) *Splash proof machines:* These are protected against penetration of solid bodies and of water falling vertically on the machines.
- (d) *Totally enclosed machines:* These are protected by enclosures without openings but are not airtight.
- (e) *Airtight or hermetically sealed machines:* These are totally enclosed machines; there is no communication between the interior of the machines and the surrounding medium.
- (f) *Flame proof or explosion proof machines:* These machines are so constructed that if there is any explosion within the machine, it will not be transmitted to the outside surroundings. This prevents injuries to the workers and the fire hazards in risky locations.

3.8 METHODS OF VENTILATION AND COOLING

It is necessary to provide suitable ventilation and cooling for the machines so that the temperature rise at any part of the machine does not go beyond the permissible limit depending on the type of insulation used in the construction. Electrical machines are also classified depending on the type of ventilation and cooling system used for the machines.

The cooling of electrical machines by means of an air-stream is called ventilation of the machines.

The circulation of air in the machine can be arranged by the use of a built-in fan or a fan with a separate drive. Either a centrifugal type fan or an axial type fan is used for electrical machines. A centrifugal fan forces air from the centre to flow outwards and operates the same way irrespective of the direction of rotation of the machine. An axial or propeller type fan moves the air in the opposite direction when the direction of rotation of the machine changes.

- (a) Machines with an *open-circuit ventilation system* are those in which heat is given up directly to the cooling air; the air is being replaced continuously.
 - (i) In *self-ventilated machines*, the internal surface of the machine is cooled by a built-in fan in the machine.
 - (ii) Machines with *natural cooling* have air movements in the machine due to its rotation or due to the temperature difference between inside parts and the outside temperature of the air.
 - (iii) Separately ventilated electrical machines are cooled by means of fans with a separate drive from outside.
 - (iv) In *ventilated frame electrical machines*, the external surface of the frame is cooled by a built-in fan.

Figure 3.22 shows the suction ventilation method used in electrical machines.

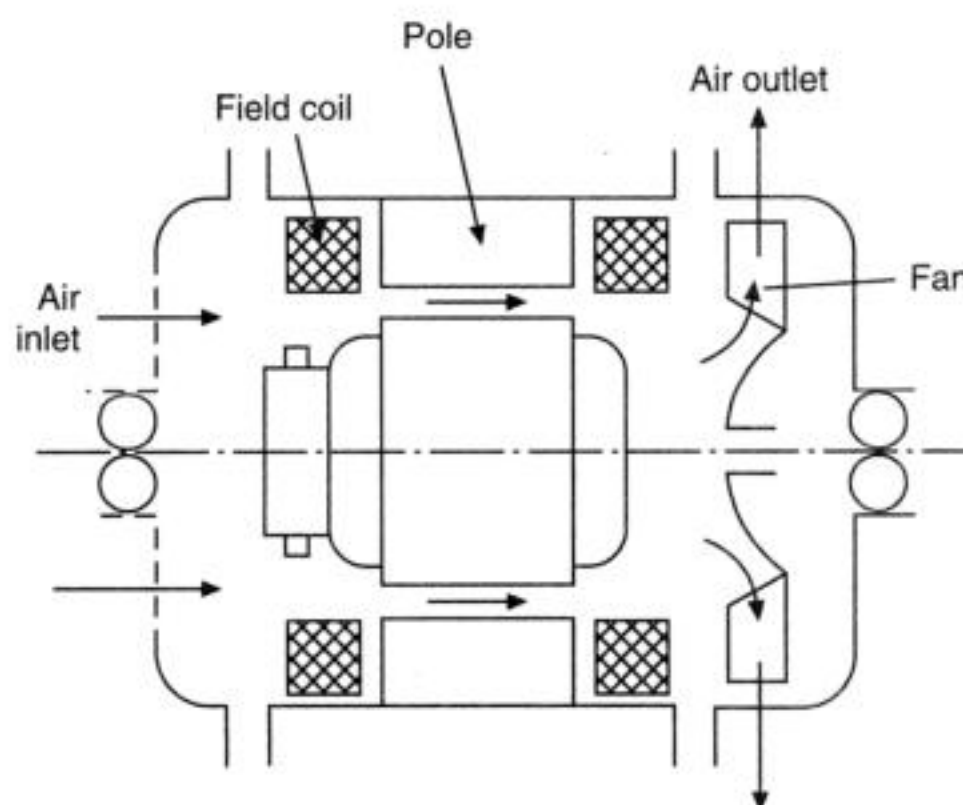


Figure 3.22 Suction ventilation method used in electrical machines.



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- (iii) Corrugated tanks.
- (iv) Tanks with regulators.

(b) *Forced oil cooling:*

- (i) Forced air blast cooling can be used; a hollow-walled tank is used and the cooling air is blown through the hollow space.
- (ii) Oil pump is used to force oil through the transformer and radiator. The radiator is cooled by a fan.

Conservators are used with the main tanks or radiator tanks of transformers. The conservator consists of an air-tight cylindrical metal drum supported on the transformer lid or radiator top. Conservator is required to take up the expansion and contraction of oil due to temperature variation in service. This is to avoid having the oil to come in contact with the outside air from which it is likely to absorb moisture. Displacement of air due to the change of oil volume takes place through a *breather*; the breather contains calcium chloride or silica gel which attracts moisture from the air.

- (iii) Another method of forced cooling for very large size transformers is to use a separate heat exchanger to cool the radiator by circulating water. The oil in the radiator and main transformer tank is circulated by an oil pump.

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Design of Magnetic Circuits: Field System

4.1 CALCULATION OF MAGNETIC CIRCUITS

The magnetic circuit for a machine is divided into series and parallel circuits and each part of the circuit is considered while solving the magnetic circuit. The flux in the air-gap is determined from machine design requirements such as voltage, ampere-conductors on the armature, etc. The flux distribution in the parts of the magnetic circuit is then found out; the ampere-turns required to produce that flux in each part is calculated by simple magnetic laws, and then they are added together to find the total ampere-turns required in order to have flux in the air-gap corresponding to the starting point.

Knowing the flux in each part of the circuit, the flux density in that part is found out and checked to find out if it is within the permissible limits for the material used for the part.

Core losses are found out from the type of material used, thickness of the material, and the frequency of flux variation to which it is subjected. Curves are available for hot rolled and cold rolled steels of different thicknesses. The curves give watts per kg. We need to find the weight of the part and then the total loss.

4.1.1 Permissible Flux Densities

The maximum permissible flux densities for the various materials used for machine parts of magnetic circuits are as follows:

- (a) Core plates at 50 Hz; max. B in teeth: 1.8 to 2.0 Wb/m²; max. B in cores: 0.8 to 1.5 Wb/m².

For transformers: 1.2 to 1.7 Wb/m² depending on the size of the transformer and the quality of steel laminations used.

- (b) Cast steel: for poles, 1.7 to 1.9 Wb/m²; for yokes, 1.4 to 1.5 Wb/m².
- (c) Cast iron: for yokes, 0.7 Wb/m².
- (d) Air-gap: average flux density for alternating flux: 0.5 to 0.7 Wb/m²; when the flux is steady; max. flux density, 1.1 Wb/m².

The magnetization curves of flux density B_m vs. ampere-turns per metre are given for various types of the materials used in magnetic circuits. For each part of the circuit we find the ampere-turns/m for the corresponding flux density in the circuit part and then find the length of the magnetic path in the circuit; ampere-turns/m multiplied by the length gives the ampere-turns in that part. If the ampere-turns for all the parts of the magnetic circuit are added, the result gives the ampere-turns required to produce the flux in the required magnetic parts.

4.1.2 Parts in the Magnetic Circuit of a Machine

The notations used for the calculation of magnetic circuit ampere-turns, etc. are as follows:

ϕ = magnetic flux in Wb

A = area of flux path in m²

B = flux density in Wb/m² = $\frac{\text{flux}}{\text{area}} = \frac{\phi}{A}$

$F = AT$ = total ampere-turns = ampere-turns/m $\times$ length in metres

$\mu = \mu_0 \mu_r$ where $\mu_0 = 4\pi \times 10^{-7}$ henries/m;

μ_r = relative permeability

$\mathcal{R}$ = reluctance = $\frac{1}{A\mu}$ ampere-turns per weber

p = permeance = $\frac{1}{\text{reluctance}} = \frac{1}{\mathcal{R}} = \frac{A\mu}{e}$

λ = leakage coefficient = $\frac{\text{useful flux} + \text{leakage flux}}{\text{useful flux}}$

The parts of the magnetic circuits are:

- (a) Air-gap
- (b) Core
- (c) Teeth
- (d) Pole
- (e) Yoke

If ϕ webers is the flux in the air-gap; the flux through the core is $\phi/2$; flux through the teeth = ϕ ;

Flux through each tooth = $\frac{\text{Flux per pole } \phi}{\text{Number of teeth under the pole}}$

Flux through the pole = $\lambda\phi$; $\lambda = 1.15$ to 1.2

Flux through the yoke = $\frac{\lambda\phi}{2}$

MMF = flux $\times$ reluctance = $\phi \times \mathcal{R}$

$$\frac{B \times A \times l}{A\mu} = \frac{B}{\mu} \times l = Hl = \text{ampere-turns per metre (at)} \times l \quad (4.1)$$

Total mmf $F = AT = (at_1)l_1 + (at_2)l_2 + \dots$ for a series circuit where at_1, at_2 , etc. are ampere-turns per metre from the curves of the magnetic materials for the corresponding flux densities in the parts and l_1, l_2 , etc. are lengths in metres of the magnetic paths in the parts.

For air and nonmagnetic materials,

$$\mu_r = 1, B = \mu_0 H \text{ or } H = at = B/\mu_0 = (0.8 \times 10^6) B \text{ ampere-turns per metre as } \mu_0 = 4\pi \times 10^{-7}. \quad (4.2)$$

(a) *Air-gap:* For a smooth air-gap between two magnetic cylindrical surfaces of stator and rotor or pole and armature, the above approximate relation for calculation of ampere-turns is valid. However, in practice, either or both surfaces may have slots or variation of the air-gap length in part of the surrounding surfaces. The method of calculating reluctance of air-gap is not then very accurate and account has to be taken of these dents in either or both surfaces. This is done by the use of Carter's coefficient.

Figure 4.1(a) shows the effect of flux distribution in the case of open type slots and Figure 4.1(b) shows the case of semi-closed slots on both surfaces.

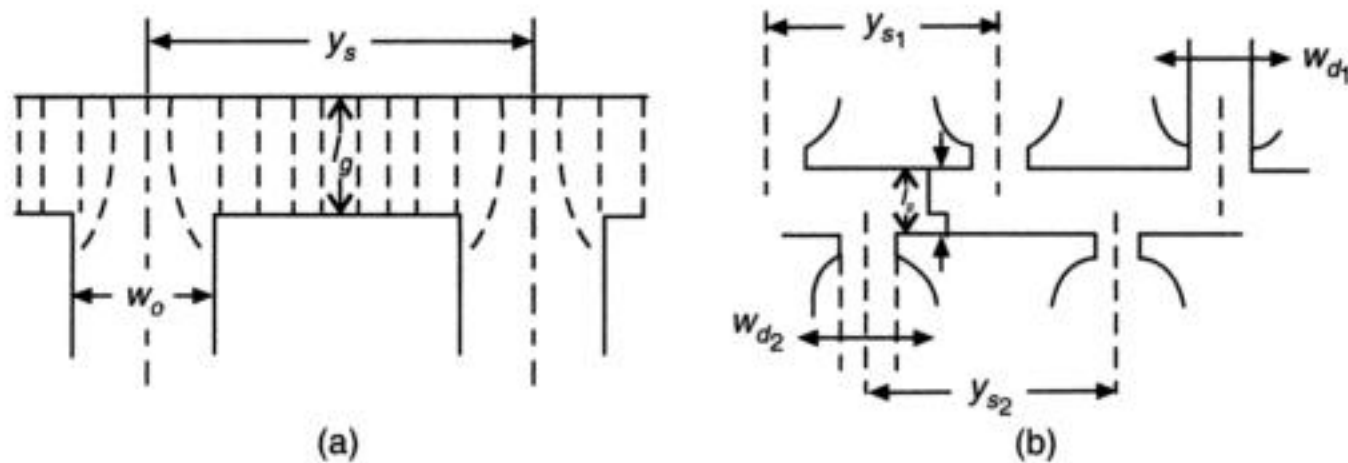


Figure 4.1 (a) Open slots and (b) semi-closed slots.

The effect of slot openings is to increase the reluctance by contraction of the flux. The effect of slotting depends on the width of the opening and the length of the air-gap. A similar effect is also caused by the ducts openings in the surfaces on either side.

Let L = core length in m
 l_g = length of air-gap in m
 y_s = slot pitch in m
 w_o = slot opening in m
 w_d = width of ventilating duct in m
 n_d = number of ventilating ducts.

The effective width of the flux path through the slot pitch y_s is reduced to y'_s and is given by

$$y'_s = y_s - k_o w_o \quad (4.3)$$

where k_o is Carter's coefficient. Similarly, the radial duct openings can be accounted for by considering the contracting axial length L of the gap surface to L' where

$$L' = L - k_d n_d w_d \quad (4.4)$$

When both the surfaces are slotted as in the case of induction motor stator and rotor slots on either side of the air-gap, the air-gap length l_g can be considered to be lengthened to l'_g to allow for the increased reluctance of the air-gap due to slot openings. The Carter's coefficient vs. the ratio of opening/gap is shown in Figure 4.2.

Then

$$l'_g = k_g l_g \quad (4.5)$$

where

$$k_g = k_{g1} \times k_{g2}; \quad k_{g1} = \frac{y_{s1}}{y_{s1} - k_{o1} w_{o1}};$$

$$k_{g2} = \frac{y_{s2}}{y_{s2} - k_{o2} w_{o2}} \quad (4.6)$$

k_{o1} and k_{o2} are functions of $\frac{w_{o1}}{l_g}$ and $\frac{w_{o2}}{l_g}$ respectively and are obtained from the curves in Figure 4.2.

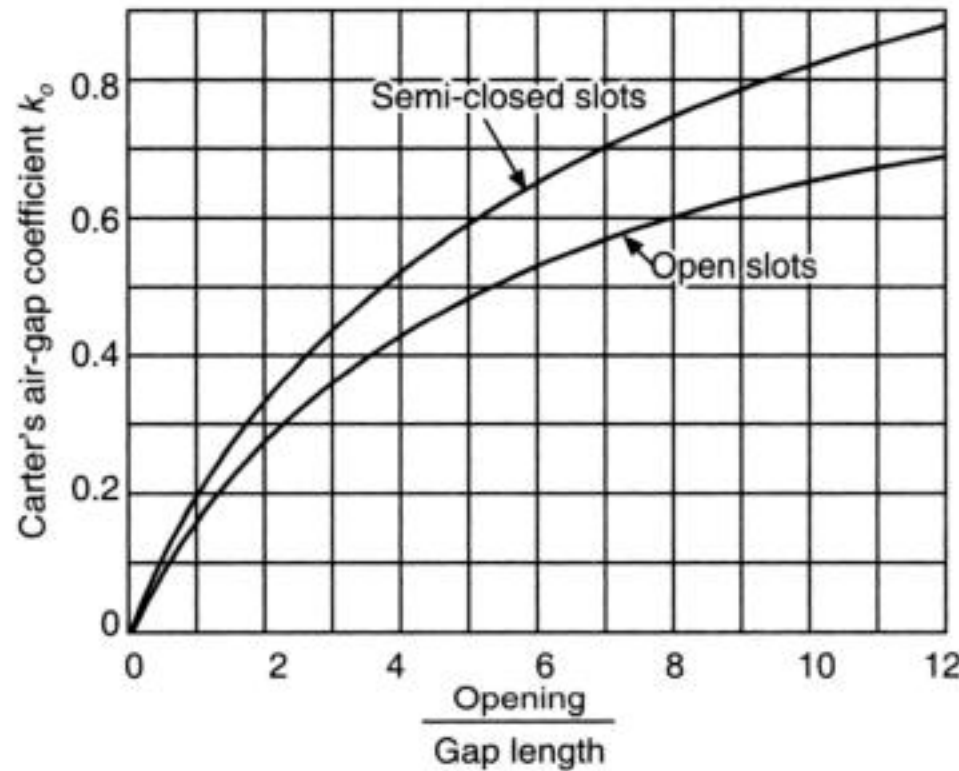


Figure 4.2 Carter's coefficient for air-gaps.

Then the ampere-turns for air-gap of the salient pole machine are given by

$$AT = 0.8 \times 10^6 K_g B_g l_g \quad (4.7)$$

where l_g is the air-gap length at the centre of the pole in m, B_g is the maximum flux density

at the centre of the pole, $K_g = \frac{L}{L'} \times \frac{y_s}{y'_s}$

This takes into consideration the effect of openings due to slots and ducts.



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Armature core: Outside diameter 0.55 m; Inside diameter of core 0.28 m; Length of armature core (gross) 0.25 m; Duct in core 3; Width of duct 0.009 m; Area of core 0.018 m²; Length of magnetic path 0.10 m.

Armature teeth: Number of slots 61; Slot pitch 0.0284 m; slot opening 0.01 m; depth of slot 0.044 m; number of teeth per pole 10.17; effective teeth per pole = 7.1 (teeth under the pole arc); area of teeth under the pole arc = 0.025 m² taking section at 1/3 length of the tooth from the smallest width. Pole arc/pole pitch = 0.7; effective pitch of tooth 0.025 m; effective width 0.015 m.

Pole: Axial length 0.25 m; Breadth 0.14 m; Area of pole 0.035 m²; Leakage coefficient 1.15; Length of magnetic path 0.18 m.

Yoke: Leakage coefficient 1.2; Area of yoke section 0.022 m²; Length of magnetic path 0.26 m; Air-gap 0.004 m.

Solution:

Figure 4.6 shows the distribution of magnetic flux in the various parts of the dc machine. The ampere-turns required for each part will be found out separately and then added.

Armature core: Flux in the armature core $\phi/2 = (0.05/2)$ Wb. Area of core = 0.018 m².

$$\text{The flux density in core } B_c = \frac{0.05}{2 \times 0.018} = 1.39 \text{ Wb/m}^2$$

Referring to the curve (i) of special Lohys (1) (Figure 4.4),
at for $B_c (= 1.39 \text{ Wb/m}^2) = 800$

Length of magnetic path in armature core = 0.10 m

Therefore, ampere-turns for core $AT_{\text{core}} = 800 \times 0.10 = 80$

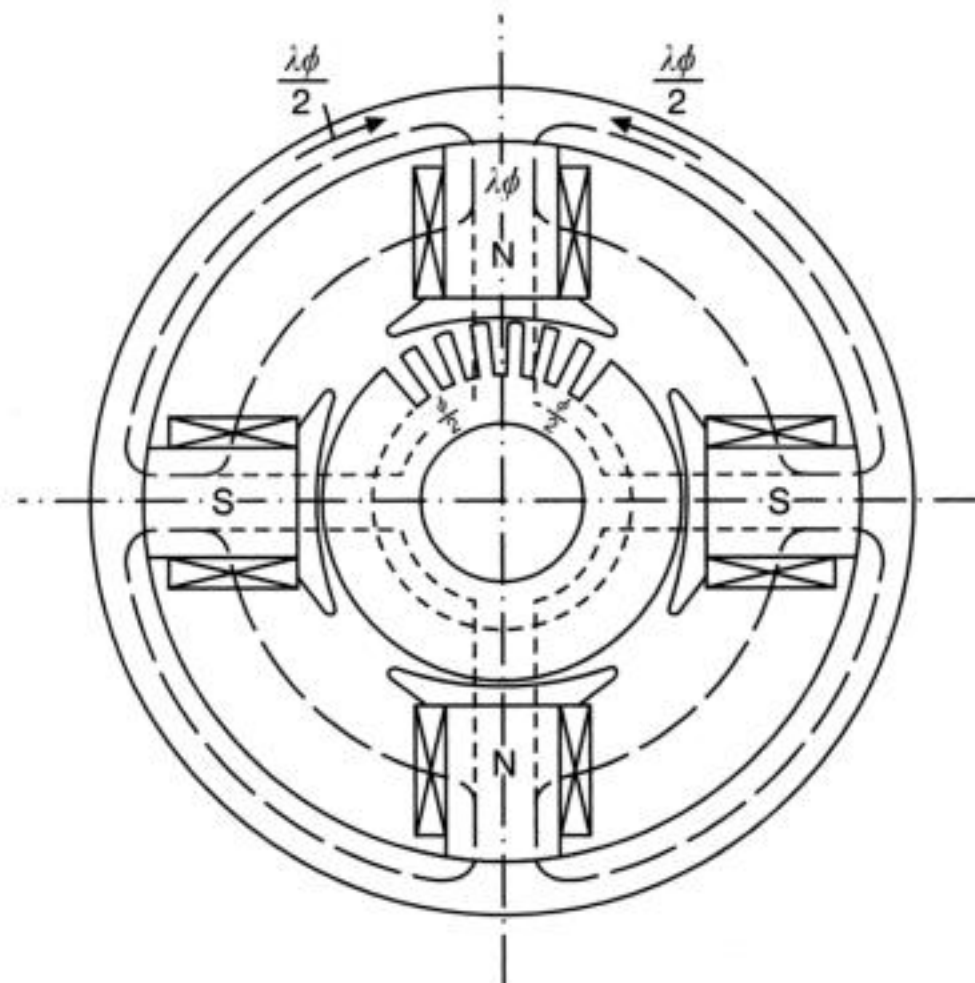


Figure 4.6 Magnetic paths in dc machine (not to scale).



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Flux density in the air-gap at the centre of the pole

$$B_g = B_{av} \times \frac{1}{0.7} = 0.7 \times \frac{1}{0.7} = 1 \text{ Wb/m}^2$$

Slot pitch $y_s = 0.0284 \text{ m}$

Slot opening $w_o = 0.01 \text{ m}$; $\frac{\text{Slot opening}}{\text{Length of air-gap}} = \frac{0.01}{0.004} = 2.5$

From Figure 4.2 for open slots of the armature in case of dc machine, $K = 0.34$ for slot opening to slot width ratio of 2.5.

Due to air-gap and ventilation ducts, $K_{g_v} = \frac{L}{L - 3 \times 0.009 \times k_v}$

$$\frac{\text{Ventilating duct width}}{l_g} = \frac{0.009}{0.004} = 2.25$$

From the curve for this ratio of 2.25, $k_v = 0.3$

Substituting,

$$K_{g_v} = \frac{0.25}{0.25 - 0.0008} = 1.033$$

$$K_{g_s} = \frac{y_s}{y_s - k_o w_o} = \frac{0.0284}{0.0284 - 0.34 \times 0.01}$$

$$= \frac{0.0284}{0.0250} = 1.136$$

$$K_g = 1.136 \times 1.033 = 1.174$$

$$\begin{aligned} \text{Ampere-turns for air-gap, } AT_{\text{air}} &= 0.8 \times 10^6 \times B_g \times K_g \times l_g \\ &= 0.8 \times 10^6 \times 1 \times 1.174 \times 0.004 \\ &= 3757 \end{aligned}$$

$$\begin{aligned} \text{Total ampere-turns per pole} &= AT_{\text{core}} + AT_{\text{teeth}} + AT_{\text{pole}} + AT_{\text{yoke}} + AT_{\text{air}} \\ &= 80 + 880 + 540 + 286 + 3757 \\ &= 5543 \end{aligned}$$

Thus the excitation required by the dc machine on no-load is 5543 ampere-turns per pole. If the effect of armature reaction is given or calculated with the data obtained for the purpose, the total ampere-turns per pole required on given load—full load—can be calculated. This is ampere-turns on no-load plus the ampere-turns required to overcome the effect of armature reaction.

The calculation of ampere-turns for various parts in the magnetic circuit can be summarized and tabulated as follows:

*Magnetic circuit*Flux per pole in air-gap $\phi = 0.05$ Wb (dc machine)

Part	Area (m ²)	Length (m)	Flux (Wb)	Flux density (Wb/m ²)	at (ampere-turns/m)	(AT)
Core	0.018	0.10	0.025	1.39	800	80
Teeth at 1/3rd length	0.025	0.044	0.05	2.0 (apparent) 1.96 (real)	20000	880
Air-gap	0.05	0.004	0.05	1.00	940000	3757
Pole	0.035	0.18	0.0575	1.64	3000	540
Yoke	0.022	0.26	0.03	1.36	1100	286
Total ampere-turns per pole, AT = 5543						

EXAMPLE 4.2 Find the ampere-turns excitation required per pole for a salient pole synchronous generator with the following data.

Work out excitation on no load.

Flux in air-gap per pole, 0.12 Wb. 10 pole synchronous generator. Stator: diameter at air-gap, 2 m; gross length of core, 0.4 m; 5 ducts each 0.01 m wide; area of core, 0.045 m²; mean length of magnetic path: This may be taken as half the pole pitch on mean diameter.

Number of slots, 144; slot pitch 0.042 m, width of slot 0.02 m, rectangular slots; depth of slot 0.12 m;

Width of tooth at (1/3rd) length from the narrowest section, 0.023 m; area of teeth 0.075 m²; air-gap 0.012 m;

Pole: Pole arc 0.40 m; pole section 0.40 × 0.35 m²; length of path 0.2 m; leakage coefficient 1.15;

Yoke: Area 0.07 m²; leakage coefficient 1.15; length of magnetic path, 0.2 m.

In the case of a synchronous machine, poles are on the rotor fixed on the rotor spider or yoke. The ampere-turns for rotor yoke are negligible.

Solution:

Stator core:

$$\text{Flux in stator core} = \frac{1}{2}\phi = \frac{0.12}{2} = 0.06 \text{ Wb}$$

Area of core = 0.045 m²; Flux density in core, $B_c = \frac{0.06}{0.045} = 1.33 \text{ Wb/m}^2$. The stator laminations are of special Lohys.

Referring to the dc magnetization curve of special Lohys, find the ampere-turns/m for $B_c = 1.33 \text{ Wb/m}^2$; ampere-turns/m = 520; mean length of path in stator core = 0.34 m.

Therefore, ampere-turns for the core, $AT_{\text{core}} = 520 \times 0.34 = 177$.

Stator teeth:

Flux = 0.12 Wb tooth width at 1/3; length from narrowest section = 0.023 m; area of teeth = 0.075 m²;

$$\text{Apparent flux density} = \frac{0.12}{0.075} = 1.6 \text{ Wb/m}^2$$

$$K = \frac{\text{Pole pitch}}{\text{Pole arc}} \times \frac{L}{L_i}$$

$L = 0.4$ m; 5 ducts each 0.01 wide; net length = $0.4 - 5 \times 0.01 = 0.35$ m; stacking factor = 0.9; net iron length = $0.35 \times 0.9 = 0.315$ m.

$$K = \frac{1}{0.7} \times \frac{0.4}{0.315} = 1.81$$

From the curve of apparent density vs. ampere-turns/m and also real flux density which will be obtained when $K = 1.81$; real flux density in teeth = 1.65 Wb/m²; and ampere-turns/m = 8000; length of magnetic path = depth of tooth = depth of slot = 0.12 m. Therefore, ampere-turns for teeth, $AT_{\text{teeth}} = 8000 \times 0.12 = 960$. Stator core and teeth laminations are taken as of special Lohys.

Air-gap:

Length of air-gap = 0.012 m; flux in air-gap = 0.12 Wb per pole. Total flux in air-gap space all along the circumference of the rotor = $0.12 \times 10 = 1.2$ Wb. Diameter at the gap = 2 m; length = 0.4 m. Average flux density $\bar{B}$ in air-gap

$$= \frac{1.2}{\pi \times 2 \times 0.4} = 0.4775 \text{ Wb/m}^2$$

Flux density at the centre of the pole where air-gap is minimum, is the maximum flux density in the air-gap and is given by

$$B_g = \bar{B} \times \frac{\text{Pole pitch}}{\text{Pole arc}} = 0.4775 \times \frac{1}{0.7} = 0.682 \text{ Wb/m}^2$$

$$\frac{\text{Slot opening}}{l_g} = \frac{0.02}{0.012} = 1.67$$

From the curve for open slots,
Carter's coefficient $k_o = 0.26$

$$\text{Slot coefficient} = K_s = \frac{0.042}{0.042 - 0.02 \times 0.26} = 1.135$$

Effect of duct opening : Width of duct = 0.01 m

$$\frac{\text{Width}}{l_g} = \frac{0.01}{0.012} = 0.833; \quad k_d = 0.12$$

$$K_d = \frac{0.4}{0.4 - 5 \times 0.01 \times 0.12} = \frac{0.4}{0.3940} = 1.015$$



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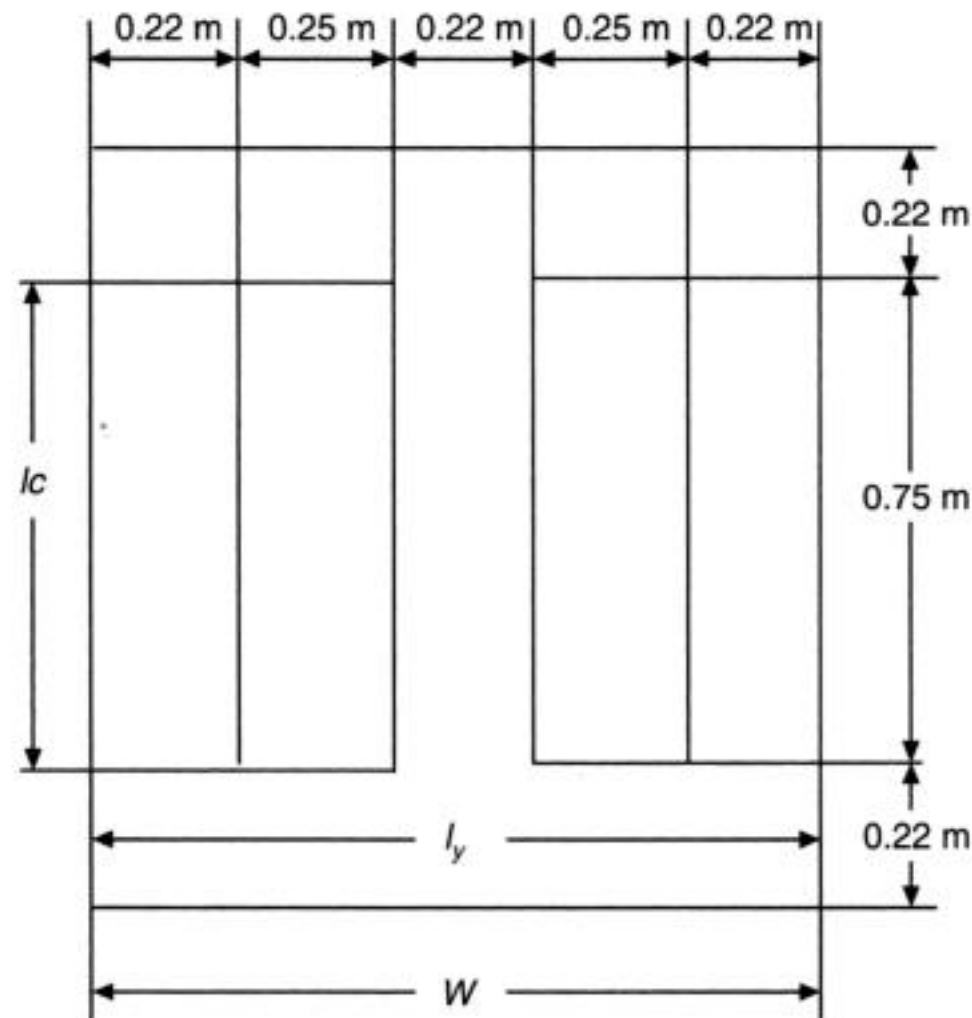


Figure 4.9 Section of the transformer of Example 4.3.

Cross-section of core, $A_c = 0.033 \text{ m}^2$

For the yoke, the area may be increased by 15%;

$$A_y = 1.15 \times 0.033 = 0.038 \text{ m}^2$$

Maximum flux density in core $B_m = \frac{\phi}{A_c} = \frac{0.043}{0.033} = 1.3 \text{ Wb/m}^2$

From the curve for hot rolled steel (Figure 4.5) for $B_m = 1.3 \text{ Wb/m}^2$, ampere-turns/m = 950

Maximum flux density in the yoke, $B_m = \frac{0.043}{0.038} = 1.13 \text{ Wb/m}^2$

From Figure 4.5, ampere-turns/m = 300

From Figure 4.9, the total width of the core

$$W = 0.22 + 0.22 + 0.22 + 0.25 + 0.25 = 1.16 \text{ m}$$

The length of magnetic path in the yoke, $l_y = 1.16 \text{ m}$

Length of core limb, $l_c = 0.75 \text{ m}$

Ampere-turns for core limb = $3 \times 0.75 \times 950 = 2137$

Ampere-turns for yoke = $300 \times 2 \times 1.16 = 696$

Total ampere-turns = $2137 + 696 = 2833$

Ampere-turns per phase = $\frac{2833}{3} = 944.3$

Magnetizing current per phase, $I_m = \frac{944.3}{\sqrt{2 \times 350}} = 0.516 \text{ A}$

Being delta connected on H.V. side, the line current (magnetizing)

$$= \sqrt{3} \times 0.516 = 0.89 \text{ A}$$

Another method of finding the magnetizing current of a transformer is to find out the weight of iron used in the core and yoke. Knowing the cross-section of the core and yoke, also the length of core and yoke, the volume of the iron used can be determined; Density of iron = 7.8 g/cm^3 .

Figure 4.10 shows the relation of VA/kg vs. B for hot rolled and cold rolled laminations. Knowing the flux density to which the magnetic part is subjected, and its weight, the volt-ampere per kg is found out. Knowing the volt-amperes for all parts—here core and yoke—and the voltage of the transformer, amperes taken for magnetizing purposes can be determined.

The method of testing and obtaining the curves as in Figure 4.10 was explained in an earlier chapter.

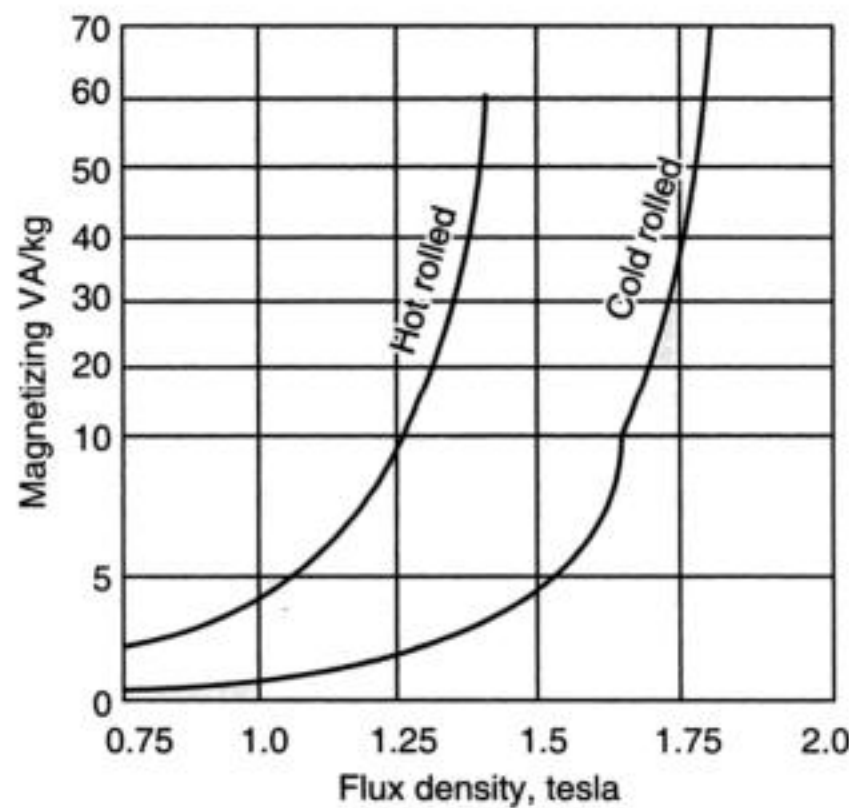


Figure 4.10 VA/kg vs. B .

4.2.2 Magnetizing Current of Induction Motors

The summation of ampere-turns for the several series parts of magnetizing circuit in the machine gives the total excitation to be provided by the exciting winding of the machine. For three-phase machine with uniformly distributed windings with 60° phase spread, and carrying sinusoidal currents, the mmf is nearly sinusoidal. The peak value of mmf F_a is related to the magnetizing current (rms) value I_m (per phase) by

$$F_a = \frac{2.7 I_m T_{ph} K_w}{p} \text{ ampere-turns per pole} \quad (4.16)$$

where

p = number of poles

I_m = magnetizing current per phase

T_{ph} = number of turns per phase
 K_w = winding factor.

or the magnetizing current
$$I_m = \frac{AT \times p}{2.7 K_w T_{ph}} \text{ A} \quad (4.17)$$

In the case of induction motors, the flux distribution is not exactly sinusoidal; the flux has pronounced flattening due to the tooth saturation effect. The flattened flux density curve can be considered as a curve with a fundamental superimposed by third harmonic flux. If we consider the point on the curve at 30° from the point of maximum flux density position, the value of flux density at 30° , B_{30} will be fairly accurate for emf calculation and there will not be an error by considering this value of B . The nature of the curve for flux distribution is shown in Figure 4.11.

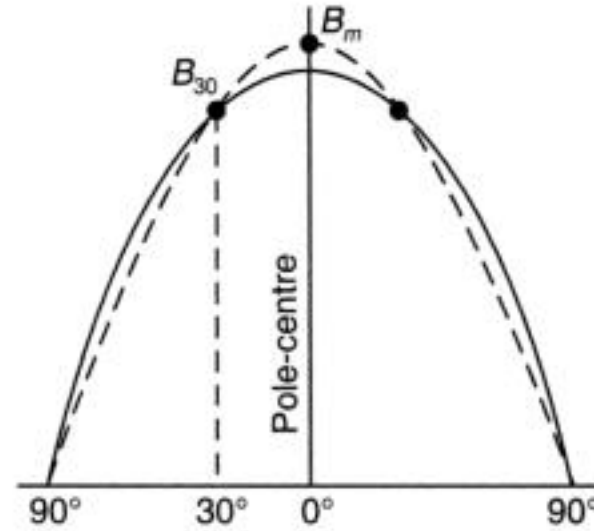


Figure 4.11 Air-gap flux distribution in an induction motor.

$$\text{The value of } B_{30} = B_1 \cos 30^\circ = \frac{\phi_1}{A} \times \frac{\pi}{2} \times \frac{\sqrt{3}}{2}$$

$$B_{30} = 1.36 \frac{\phi_1}{A} \quad (4.18)$$

where ϕ_1 = fundamental flux; A = area through which ϕ_1 passes. Using this flux distribution, the magnetizing current in the case of an induction motor is given by

$$I_m = \frac{pAT_{30}}{2.7 K_w T_{ph} \cos 30^\circ} = \frac{pAT_{30}}{2.34 K_w T_{ph}} \quad (4.19)$$

EXAMPLE 4.4 Calculate the magnetizing current per phase for a three-phase star connected induction motor with the following data:

Average flux density, $\bar{B} = 0.5 \text{ Wb/m}^2$; diameter, $D = 0.7 \text{ m}$; 10 poles; length of core $L = 0.25 \text{ m}$; 3 ducts in stator and rotor cores opposite to each other each 0.01 m wide; Lohys laminations 0.50 mm thick; stator slot width = 0.023 m ; slot opening = 0.003 m ; depth of slot = 0.042 m ; pole pitch $Y = 0.22 \text{ m}$; turns per phase = 250, rotor slot width = 0.017 m ; opening = 0.003 m ; depth of slot = 0.035 m ; semi-closed slots. Stator core: area = 0.012 m^2 ; length of magnetic path = 0.1 m ; stator teeth (1/3) area = 0.025 m^2 ; length of magnetic path = 0.042 m ; rotor teeth (1/3) area 0.023 m^2 ; length = 0.035 m . Rotor core: area = 0.011 m^2 ; length = 0.07 m ; Air-gap = 0.001 m .

Find the Carter's coefficients for the various openings, viz. of slots and ducts and use them in finding the ampere-turns as required.



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$$\frac{\text{Opening}}{l_g} = \frac{0.003}{0.001} = 3$$

From curve, $K_2 = 0.45$

$$\begin{aligned}\text{The effective air-gap length, } l'_g &= l_g \times k_{g_1} \times k_{g_2} \\ &= 0.001 \times 1.06 \times 1.08 = 0.00114 \text{ m}\end{aligned}$$

$$B_{30} = \frac{1.36 \times 0.0275}{0.056} = 0.668 \text{ Wb/m}^2$$

$$\begin{aligned}\text{Ampere-turns for air-gap, } AT_{\text{air}} &= 0.8 \times 10^6 \times 0.668 \times 0.00114 \\ &= 610\end{aligned}$$

Rotor teeth (at 1/3rd length):

$$\text{Area} = 0.023 \text{ m}^2; \text{ length} = 0.035 \text{ m}$$

$$B = \frac{1.36 \times 0.0275}{0.023} = 1.62 \text{ Wb/m}^2$$

From the curve, ampere-turns/m = 3000

$$AT \text{ for rotor teeth} = 3000 \times 0.035 = 105$$

Rotor core: area = 0.011 m²; length = 0.07 m

$$B \text{ in rotor core} = \frac{0.0275}{2 \times 0.011} = 1.25 \text{ Wb/m}^2$$

From the curve, ampere-turns/m = 350

$$AT \text{ for rotor core} = 350 \times 0.07 = 24.5, \text{ say } 25.$$

The summation of all the ampere-turns of the series magnetic circuit gives the ampere-turns per pole considering the position of flux wave at 30° from the centre of the pole.

This can be shown in summarized form as follows:

Flux per pole $\phi_m = 0.0275 \text{ Wb}$

Part	Area, A (m ²)	Length (m)	$B = \frac{\phi_m}{2A}$	$B_{30} = 1.36 \frac{\phi_m}{A}$	at (ampere-turn/m)	AT
Stator core	0.012	0.1	1.15	...	250	25
Stator teeth (1/3)	0.025	0.042	...	1.5	1000	42
Air-gap	0.056	0.00114	...	0.668	534,000	610
Rotor teeth (1/3)	0.023	0.035	...	1.62	3,000	103
Rotor core	0.011	0.07	1.25	...	350	25
Total AT_{30}						807

$$\text{Magnetizing current per phase } I_m = \frac{p \times AT \text{ per pole}}{2.34 \times K_w \times T_{ph}}$$



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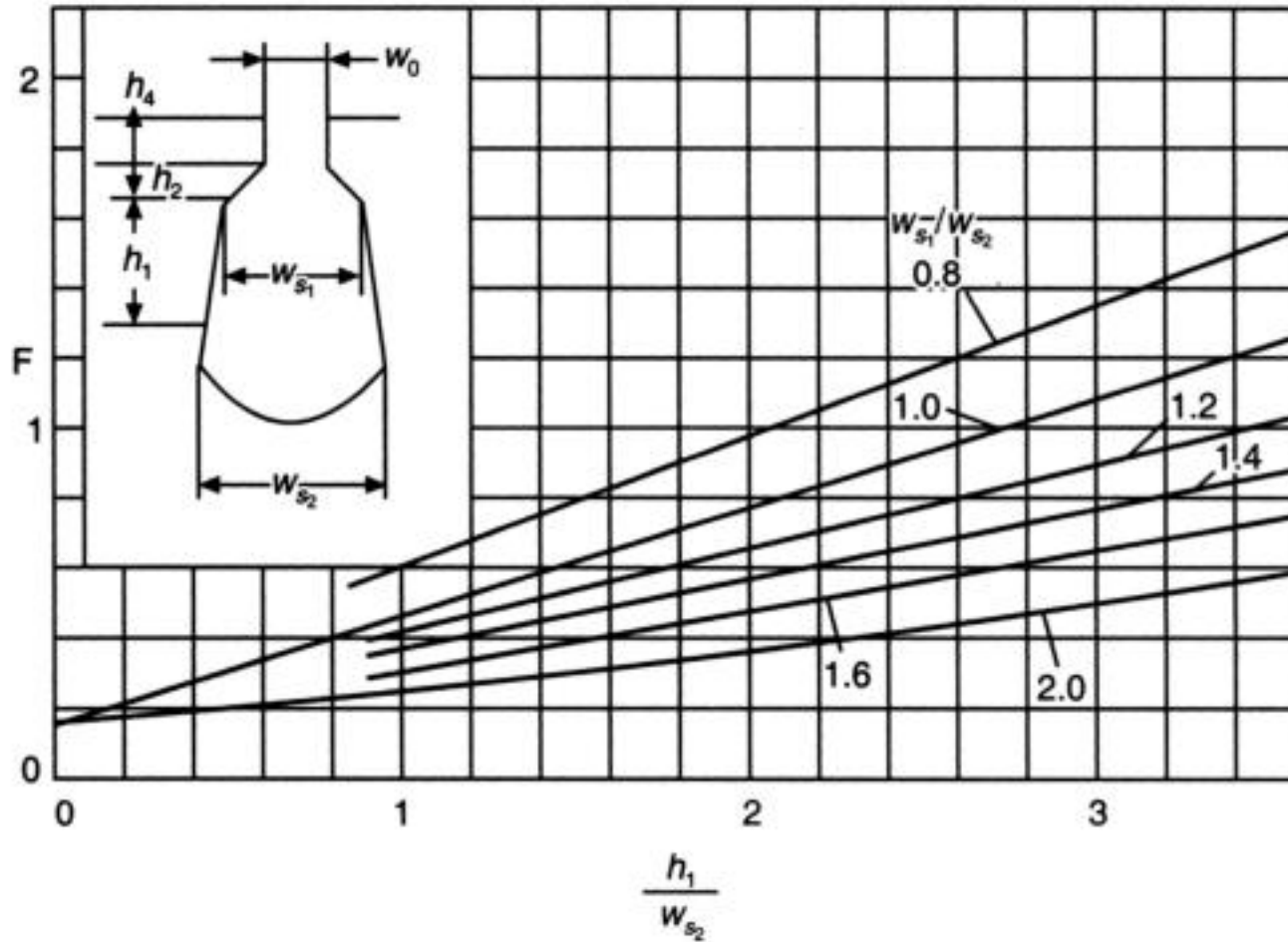


Figure 4.13(f)

Table 4.1 Values of specific permeance of slots represented in Figures 4.13(a) to (f)

$$(a) \quad \lambda_s = \frac{h_1}{3w_{s1}} + \frac{h_4}{w_o} \quad (4.24a)$$

$$(b) \quad \lambda_s = \frac{h_1}{3w_{s1}} + \frac{h_2}{w_{s1}} + \frac{2h_3}{w_{s1} + w_{s0}} + \frac{h_4}{w_o} \quad (4.24b)$$

$$(c) \quad \lambda_s = 0.66 + \frac{h_4}{w_o} \quad (4.26)$$

$$(d) \quad \lambda_s = \frac{2h_1}{3(w_{s2} + w_{s3})} + \frac{2h_2}{w_{s1} + w_{s2}} + \frac{2h_3}{w_{s1} + w_{s0}} + \frac{h_4}{w_o} \quad (4.27)$$

$$(e) \quad \lambda_s = \phi \frac{h_1}{w_{s2}} + \frac{2h_3}{w_{s1} + w_o} + \frac{h_4}{w_o} \quad (4.28)$$

$$(f) \quad \lambda_s = F + \frac{2h_3}{w_{s1} + w_o} + \frac{h_4}{w_o} \quad (4.29)$$

Overhang leakage

This is related to the shape and the length of the end conductors, spacing between stator and rotor overhangs, types of winding, etc. It is difficult to calculate this exactly. An empirical expression is used in practice to give an appropriate value.

$$\text{An appropriate expression is, } L_o \lambda_o = k_s Y^2 / \pi y_x \quad (4.30)$$



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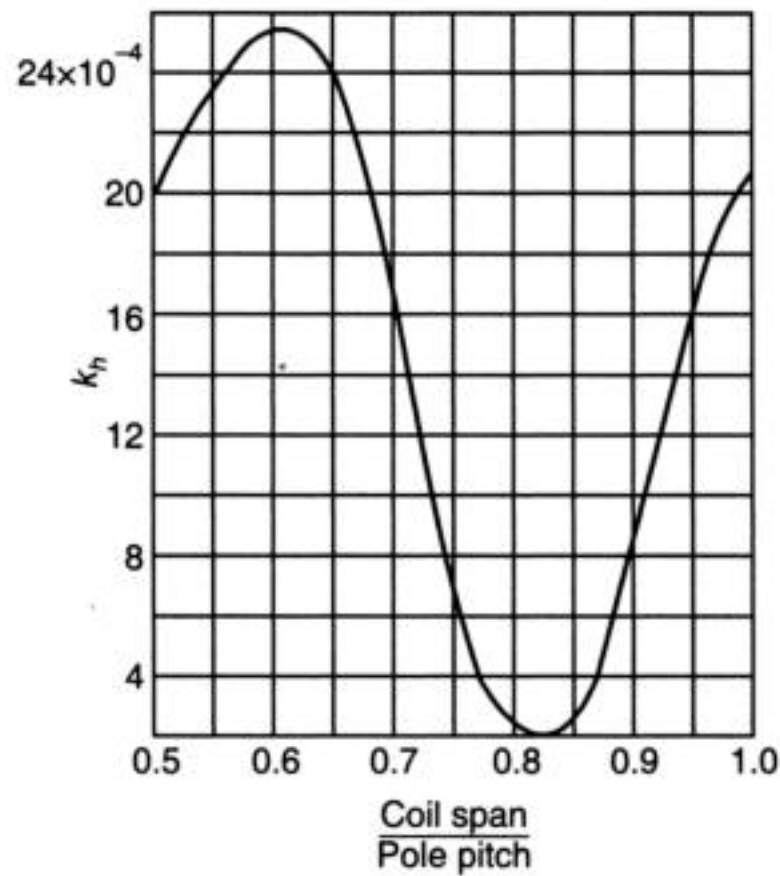


Figure 4.16 Values of k_h vs. ratio of coil span/pole pitch.

4.4.1 Reactance per Phase

$$\text{Reactance } X = 31.6 \times 10^{-6} f \frac{T_{ph}^2}{p \times g'} L \lambda \Omega \quad (4.32)$$

where

p = number of poles; f = frequency in Hz; T_{ph} = number of turns per phase; g' = number of slots per pole per phase; L = length of the conductor in core; λ = permeance coefficient.

In case of slot leakage reactance, take λ_s .

In case of overhang leakage, take $L_o \lambda_o$ instead of $L \lambda$ in the expression. The procedure to determine λ for various types of slots, etc. has already been explained in the last section.

4.4.2 Phase Reactance of an Induction Motor

Phase reactance of an induction motor referred to stator

$$X_1 = x_1 + x'_2 = x_{s_1} + x'_{s_2} + x_o + x_z + x_b \quad (4.33)$$

where x_b to be considered for wound rotor type induction motor only.

4.4.3 Phase Reactance of a Synchronous Machine

In the case of synchronous machines, it is necessary to determine the reactance for calculating the regulation.

The slot leakage and overhang leakage flux can be found out by the following expressions:

If I = full-load current in amps, and T_c = number of turns in the coil

$$\text{Slot leakage flux, } \phi_s = 2\sqrt{(2)\mu_o I T_c L_s \lambda_s} \quad (4.34)$$

and

$$\text{Overhang leakage flux, } \phi_o = 2\sqrt{(2)\mu_o I T_c L_o \lambda_o} \quad (4.35)$$

Zigzag flux is not considered in salient pole synchronous machines as the pole face is the equipotential surface in the quadrature axis.

$$\text{Total leakage flux, } \phi_l = \phi_s + \phi_o \quad (4.36)$$

EXAMPLE 4.5 Find the leakage reactance per phase of a three-phase, 50 Hz, 440 V, squirrel cage induction motor with the following data: number of poles = 4; stator slots = 36; rotor slots = 29; stator slot pitch = 0.02 m; rotor slot pitch = 0.024 m; opening of stator slot = 0.003 m; opening of rotor slot = 0.002 m; length of the air-gap = 0.0005 m; length of conductor in core = 0.18 m; shape of the stator slot ref. Figure 4.13: $w_s = 0.01$ m; $h_1 = 0.02$ m; $h_2 = 0.002$ m; $h_3 = 0.002$ m; $h_4 = 0.001$ m;

Shape of rotor slot round; diameter = 0.006 m; $h_4 = 0.001$ m (Figure 4.13). Mutual reactance $X_m = 120 \Omega$; pole pitch $Y = 0.18$ m. Full pitch winding with 60° phase belt so $K_s = 1.0$; number of turns per phase $T_{ph} = 200$.

Solution:

Stator slot permeance coefficient λ_{s_1} is given by

$$\begin{aligned} \lambda_{s_1} &= \frac{h_1}{3w_s} + \frac{h_2}{w_s} + \frac{2h_3}{w_s + w_o} + \frac{h_4}{w_o} \\ &= \frac{0.025}{3 \times 0.01} + \frac{0.002}{0.01} + \frac{2 \times 0.002}{0.010 + 0.003} + \frac{0.001}{0.003} \\ &= 0.833 + 0.2 + 0.307 + 0.333 \\ &= 1.673 \end{aligned}$$

Rotor slot permeance coefficient:

$$\begin{aligned} \lambda_{s_2} &= 0.66 + \frac{h_4}{w_o} \\ &= 0.66 + \frac{0.001}{0.002} = 0.66 + 0.5 \\ &= 1.16 \end{aligned}$$

Rotor slot permeance referred to stator:

$$\begin{aligned} \lambda'_{s_2} &= \frac{k_{w_1}^2}{k_{w_2}^2} \times \frac{S_1}{S_2} \times \lambda_{s_2} = \frac{0.96^2}{1^2} \times \frac{36}{29} \times \lambda_{s_2} \\ &= 1.158 \times 1.16 = 1.343 \end{aligned}$$

Slot leakage X_s :

$$X_s = 31.6 \times 10^{-6} \times f \times \frac{T_{ph}^2}{p \times g'} \times L_s \times (\lambda_{s_1} + \lambda'_{s_2})$$

$g' = \text{number of slots per pole per phase} = 36/(4 \times 3) = 3$. Substituting the values,

$$X_s = 31.6 \times 10^{-6} \times 50 \times \frac{200^2}{4 \times 3} \times 0.18 (1.673 + 1.343)$$

$$X_s = 2.86 \, \Omega$$

$$X_z = \frac{5}{6} \times X_m \left(\frac{1}{g_1^2} + \frac{1}{g_2^2} \right)$$

$g_1 = \text{stator slots per pole} = 36/4 = 9$

$g_2 = \text{rotor slots per pole} = 29/4 = 7.25$

Substituting the values,

$$X_z = \frac{5}{6} \times 120 \left(\frac{1}{9^2} + \frac{1}{7.25^2} \right) = 100(0.0123 + 0.019) \\ = 3.13 \, \Omega$$

For overhang leakage:

$$L_o \lambda_o = \frac{K_s Y^2}{\pi y_s} = \frac{1 \times 0.18^2}{\pi \times 0.02} = 0.515$$

$$X_o = 31.6 \times 10^{-6} \times 50 \times \frac{200^2}{4 \times 3} \times L_o \lambda_o \\ = 5.266 \times 0.515 = 2.71 \, \Omega$$

Reactance of the induction motor per phase

$$X_1 = X_s + X_z + X_o \\ = 2.86 + 3.13 + 2.71 \\ = 8.70 \, \Omega$$

EXAMPLE 4.6 Find per unit leakage reactance of a three-phase, 50 Hz, 1000 kVA, 3300 volts, star-connected alternator running at 375 rpm. Number of slots per pole per phase = 3. Concentric winding is used and the conductors per slot = 5. The average flux density, $B = 0.6$ Wb/m²; core length = 0.38 m; 3 ducts each of 0.01 m; pole pitch $Y = 0.30$ m; air-gap = 0.006 m. The stator slot is of the shape shown in Figure 4.12.

The dimensions are as follows:

$$h_1 = 0.035 \, \text{m}; h_2 = 0.005 \, \text{m}; h_3 = 0.003 \, \text{m}; h_4 = 0.0015 \, \text{m}; w_s = 0.010 \, \text{m}; w_o = 0.003 \, \text{m}.$$



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Here the width and the length of each square is made equal as far as possible so that each square represents permeance corresponding to

$$\frac{1}{\mu_0} \quad \text{or} \quad \frac{1}{4\pi \times 10^{-7}}$$

- (i) The number of squares along the air-gap, e.g. 6 in Figure 4.18 represents the permeance in series (m) while the number of squares in the air-gap along the pole pitch, e.g. 52×2 in Figure 4.18 represent permeance in parallel (n). Thus the permeance of the air-gap path under each pole of the machine is given by

$$\frac{1}{\mu_0} \times \frac{n}{m} \quad (4.38)$$

In the problem of Figure 4.18, it is $p = \frac{10^7 \times 104}{4\pi \times 6} = 1.38 \times 10^7$

- (ii) For finding the flux density distribution in the air-gap, choose a number of points along the armature periphery of width a_x . Consider tubes of force from armature surface to pole. If b_x is the mean width of the tube and δ_x is the mean length of air-gap at the point considered, permeance of the tube is proportional to b_x/a_x and the flux density at the point B_x for the armature surface width a_x and of unit length is proportional to b_x/δ . If B_g is the air-gap flux density at the centre of the pole, and air-gap length is δ , then B_g is proportional to $1/\delta$.

Thus
$$B_x = \frac{b_x}{a_x \delta} \times B_g \quad (4.39)$$

Calculate flux density at various points each 10° or 15° apart on the armature surface and flux density B vs. points considered.

Flux distribution factor, $f_d = \frac{\text{Area under the flux distribution curve}}{\text{Area under rectangle with maximum flux density}} \quad (4.40)$

- (iii) In the case of synchronous machines harmonics in flux waveform need to be determined, find the average and rms values of the flux densities from the curve over the pole pitch area, their ratio $\frac{B_{\text{rms}}}{B_{\text{av}}}$ gives the form factor of the field distribution in the air-gap.

Flux plotting is thus a useful tool in determining the above information.

4.6 OPEN-CIRCUIT CHARACTERISTICS

The open-circuit characteristics or open-circuit saturation curve gives the relation between the terminal voltage at no load and the corresponding ampere-turns per pole. The method of calculating the ampere-turns for a given voltage and thus flux conditions is explained above in

earlier sections. The air-gap ampere-turns vary directly with the voltage; for other magnetic circuits parts, the flux densities in the parts should be calculated which are directly proportional to the voltage considered, then find the ampere-turns for that value of flux density in the part; add up ampere-turns for the air-gap and various magnetic parts as in previous cases. Repeat for 100%, 120%, 130% and 150% or so and plot voltage vs. ampere-turns per pole. This is the open-circuit saturation curve.

In the case of dc machines, allow about 10% for armature reaction in the calculation of voltage regulation of generators on load. In the case of synchronous machines, work out the main flux, leakage flux, and armature reaction ampere-turns on full load and at the given power factor. Using the open-circuit curve and ampere-turns method, regulation of alternator can be worked out.

4.7 FIELD SYSTEM

The magnetic circuit part has already been explained. The flux density in the pole allowing for leakage flux gives the cross-section of the pole. The height of the pole should be such as to permit the ampere-turns necessary for the field winding to be accommodated in the space provided. The field winding is designed to provide the ampere-turns required for producing the necessary flux in the air-gap. In the case of a dc shunt generator, ampere-turns inclusive of armature reaction effect on full load have to be provided by the shunt field winding. In the case of a compound generator, armature reaction ampere-turns can be taken care of by the series winding which is in addition to the shunt field winding wound on the same poles. In the case of dc machines, poles are on the stationary part and need a larger surface of the field winding for dissipation of loss to be within the allowable temperature rise, say 1400 to 1800 mm² surface per watt dissipated. In the case of synchronous machines, the rotor has a field winding. The winding on the pole has to provide the ampere-turns required under full load conditions with the necessary armature reaction and working at the rated lagging power factor such as 0.8 lagging. Leakage reactance and synchronous reactance including armature reaction effect can be worked out and then regulation can be found out. Being on the rotating part, the surface of the field winding required for synchronous machine fields is about 600 mm² per watt dissipated. The other considerations are the same as in the dc field winding.

The principle is illustrated by Example 4.7.

EXAMPLE 4.7 Design a shunt field winding for a dc shunt generator from the following data:

6 pole, 500 volts, shunt generator has ampere-turns per pole 9000 inclusive of the requirement of armature reaction on full load. The dimensions of the space for winding on pole are shown in Figure 4.19(a). The pole is rectangular in shape with width of 0.2 m and depth of 0.32 m. The height of the pole is 0.2 m. About 420 V of the voltage is across the poles while the remaining 80 V is for the control resistance adjustment. Take the permissible surface as 18×10^{-4} m² per watt for a temperature rise of 35°C. Current density in the winding conductor may be about 2 A/mm². The depth of winding may be taken as 0.04 m.

The shape of the field coil is shown in Figure 4.19(b). The inside dimensions of the coil are 0.20 m × 0.32 m; while outside dimensions are 0.28 m × 0.4 m, roughly neglecting the space for insulation and the bending at the corners.

Solution:

$$\text{Mean length of turn } l_m = 0.36 \times 2 + 0.24 \times 2 = 1.2 \text{ m}$$

$$\begin{aligned} \text{Surface for heat dissipation} &= 2l_m (\text{height of coil} + \text{winding depth}) \\ &= 2 \times 1.2(0.2 + 0.04) = 0.576 \text{ m}^2 \end{aligned}$$

This is for each pole; for 6 poles $= 0.576 \times 6 = 3.456 \text{ m}^2$. If surface for loss dissipation is taken as $18 \times 10^{-4} \text{ m}^2$ per watt,

$$\begin{aligned} \text{Loss that can be dissipated by this surface} &= \frac{3.456 \times 10^4}{18} \\ &= 1920 \text{ W} \end{aligned}$$

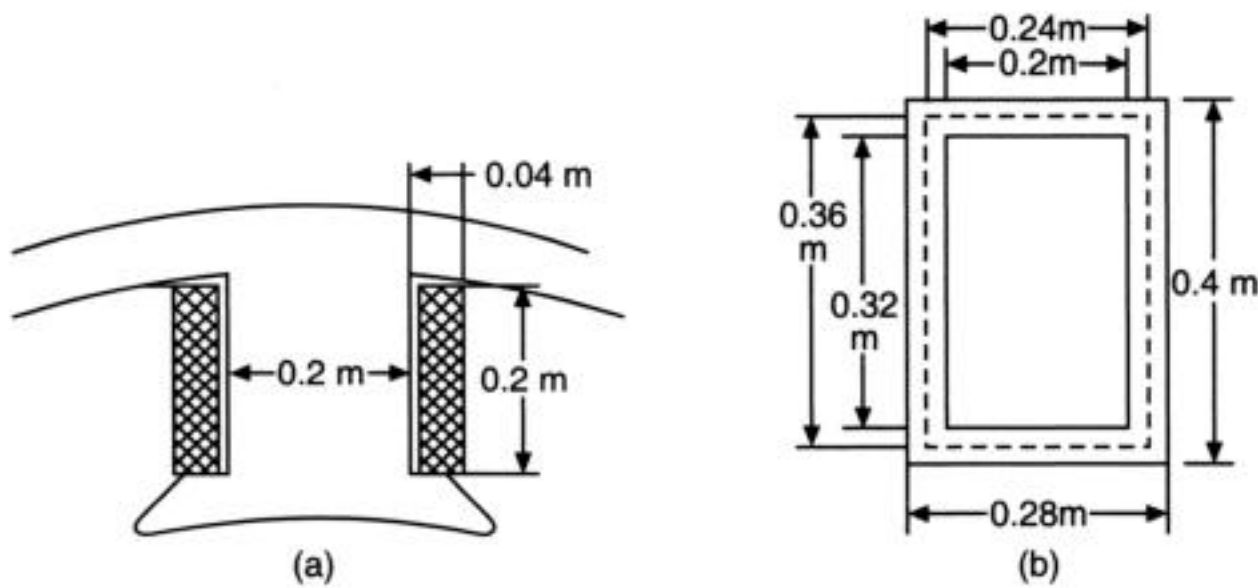


Figure 4.19 Field winding of Example 4.7.

The voltage across the poles and field winding $= 420 \text{ V}$

$$\text{The excitation current} = \frac{1920}{420} = 4.57 \text{ A}$$

$$\text{Resistance of field winding} = \frac{420}{4.57} = 91.9 \Omega$$

$$\text{Turns per pole} = \frac{\text{Ampere-turns}}{\text{Current}} = \frac{9000}{4.57} = 1969 \text{ turns}$$

$$\begin{aligned} \text{Total length of wire for field winding} &= \text{Poles} \times \text{Turns per pole} \times l_m \\ &= 6 \times 1969 \times 1.2 = 14.177 \text{ m} \end{aligned}$$

$$\text{Resistivity} = 1.7 \times 10^{-2} \Omega \text{ per mm}^2/\text{m}$$

Cross-section of the conductor for field winding

$$\begin{aligned} a \text{ (mm}^2\text{)} &= \frac{1.7 \times 10^{-2} \times 14.177}{91.7} \\ &= 2.623 \text{ mm}^2 \end{aligned}$$

From the standard conductor available from IS, choose the nearest, this is $a = 2.545 \text{ mm}^2$

The diameter of bare conductor $= 1.8 \text{ mm}$

Overall diameter of enamelled (medium) conductor $= 1.916 \text{ mm}$

Current density, $\delta = \frac{4.57}{2.545} = 1.8 \text{ A/mm}^2$ which is within the permissible limit of 2 A/mm^2 .

As height of winding is 0.2 m, the turns per layer

$$= \frac{200}{1.916} = \text{about } 100$$

Number of layers = $\frac{1969}{100} = \text{about } 20$. Make 2000 turns.

Winding depth = $1.916 \times 20 = \text{about } 0.04 \text{ m}$, which is OK. This is worked out without allowing for space for insulation and slacking factor as an approximation. In practice, this is to be accounted for.

The winding data is therefore as follows:

Number of turns per pole	2000
Number of layers	20
Number of turns per layer	100
Conductor area	2.545 mm^2
Conductor bare diameter	1.8 mm
Conductor overall diameter with enamel covering (medium)	1.916 mm

With the modified number of turns, recheck resistance, surface area, power dissipated and see that they are within the permissible limits.

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Design of Electrical Circuits: Armature Windings

5.1 ARMATURE COILS, CONSTRUCTION AND INSULATION

The coils may be single-turn or multi-turn. Copper conductors of suitable size covered with insulation are used for coils. The conductors may be round for small machines; for large size machines, square or rectangular conductors are used. The insulation on conductors may be cotton, enamel, varnished bonded glass or Class F or Class H insulation, as explained in an earlier chapter.

The coils may be random wound for small machines where round enamel conductors are generally used. The conductors are threaded in semi-closed slots. The type of coils most commonly required, however, are formed coils, i.e. they are given a required shape. The coils are given a varnish treatment for moderate voltage machines; for large size and high voltage machines, the coils are treated by a vacuum process and impregnated with a moisture resisting, heat conducting compound.

The coils may have one turn per layer where the size of the conductor is large. It is sub-divided by using several small wires in parallel. Coils with many turns may be wound as shown in Figure 5.1.

The types of coils used for ac machines are of the following shapes:

- (i) Concentric, (ii) Diamond, (iii) Hexagonal, (iv) Involute, and (v) Mush.

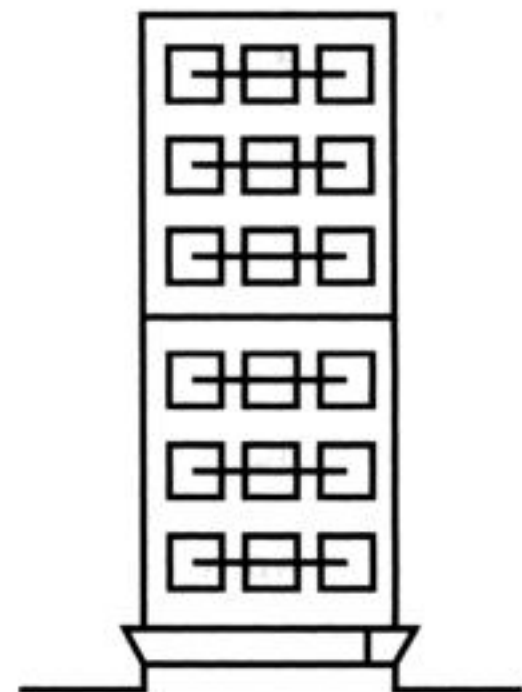


Figure 5.1 Arrangement of a multiturn coil connection.



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From the above distribution, it is seen that the repetition of consecutive conductors of each phase occurs as follows:

$$\begin{array}{ccccccc} 2 & 1 & 2 & 1 & 2 & 1 & 1 \\ 2 & 1 & 2 & 1 & 2 & 1 & 1 \\ 2 & 1 & 2 & 1 & 2 & 1 & 1 \end{array}$$

These numbers indicate phase distribution and are known as *index numbers*.

Alternative method: The layout of the fractional slot winding can also be done by reversing the process, namely by first finding the index numbers and then putting up the layout. The procedure is as follows:

Start with zero, add the denominator of the fraction successively to each number. Set down until a number results greater than the numerator. Subtract the numerator from this number. To the remainder, add the denominator again and repeat till the remainder becomes zero. Whenever the numerator is subtracted, put a mark before this, as it indicates the change of 60° phase belt.

EXAMPLE 5.3 Solve the layout for the machine in Example 5.2 by using the method of index numbers.

Solution:

Number of slots per pole per phase = $1\frac{3}{7} = \frac{10}{7}$. Layout the numbers by adding the number in the denominator starting with zero.

$$\begin{array}{ccccccccccc} & & 4 & & 1 & & 5 & & 2 & & 6 & & 3 & & 0 \\ & & (14) & & (11) & & (15) & & (12) & & (16) & & (13) & & (10) \\ 0 & & & & & & & & & & & & & & \\ & \swarrow & & \searrow & & \swarrow & & \searrow & & & & & & & \\ & 2 & & 2 & & 2 & & 2 & & & & & & & \\ & & 1 & & 1 & & 1 & & 1 & & 1 & & 1 & & \text{repeat} \end{array}$$

The distribution of the winding, therefore, as per index numbers is as follows:

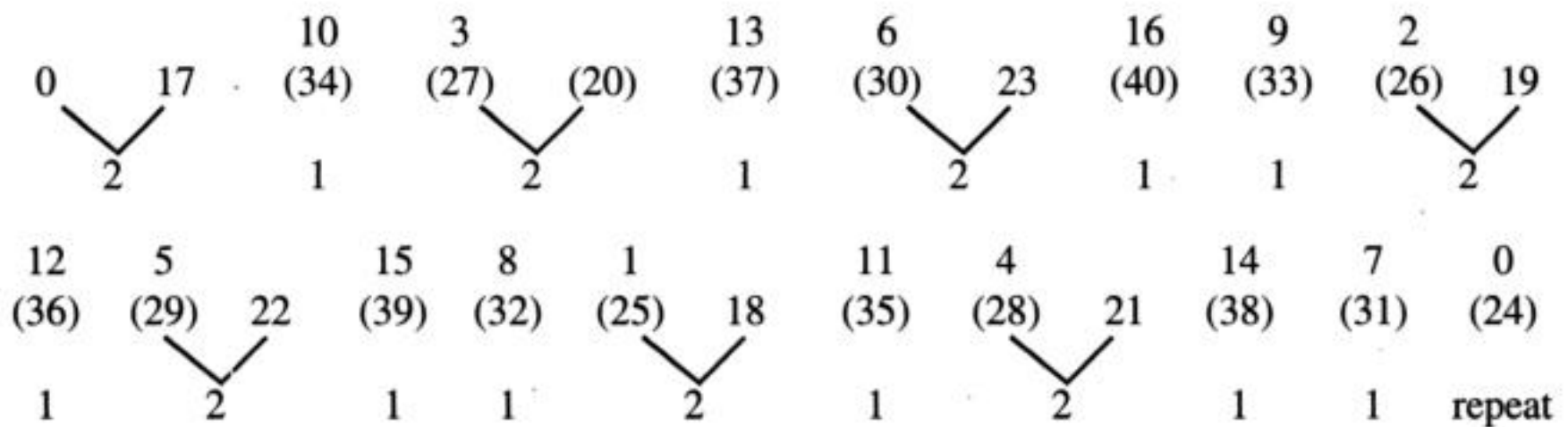
$$\begin{array}{cccccccccc} 2 & 1 & 2 & 1 & 2 & 1 & 1 & & & \\ a & a & c' & b & b & a & c' & c' & b & a \\ c' & c' & b & a & a & c' & b & b & a & c' \\ b & b & a & c' & c' & b & a & a & c' & b \end{array}$$

This distribution is the same as found in the previous example.

EXAMPLE 5.4 The number of slots per pole per phase for the winding of a particular synchronous machine is $1\frac{7}{17} = \frac{24}{17}$. Find the index numbers and show the distribution of the winding.

Solution:

$$1\frac{7}{17} = \frac{24}{17}$$



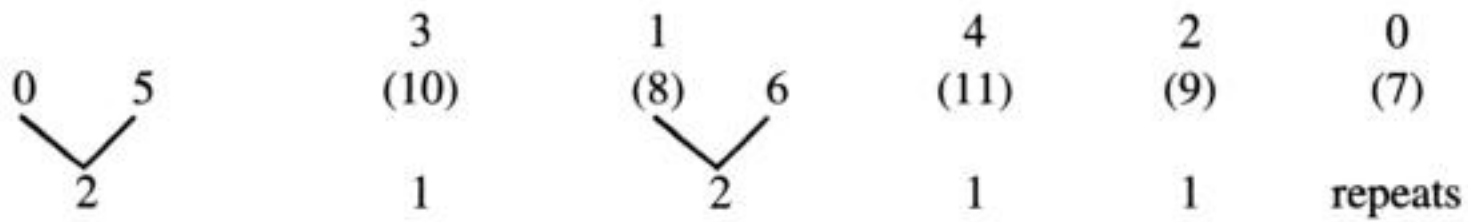
The index numbers are:

2 1 2 1 2 1 1 2 1 2 1 1 2 1 2 1 1

The distribution of conductors phasewise can then be written as in Example 5.4.

The following are some of the rules for index numbers:

- In index numbers, the number of digits must equal the denominator of the mixed fraction or the number of poles in the group whereas the sum of the index numbers will equal the numerator of the fraction, e.g. in the above example, the denominator of the improper fraction representing the number of slots per pole per phase is 17 and there are 17 digits in the index numbers for the winding as determined above. The sum of these 17 digits is 24 which is equal to the numerator of the improper fraction. This is, therefore, a check on the accuracy of the index numbers obtained.
- The numerator of the improper fraction must be prime to its denominator. For any three-phase winding, the total number of coils for the three phases is three times the numerator of the improper fraction; the denominator of the improper fraction cannot be divisible by three.
- A winding having the numerator of the improper fraction one more or one less than its denominator can have only one 2, which is written at the beginning of the index numbers.
- If the whole number of the mixed fraction is 2 instead of 1, 1 must be added to each number in the index number, e.g. if the number of slots per pole per phase is $2\frac{3}{7}$ slots, then the index numbers will be found by adding 1 to each index number of the winding for $1\frac{3}{7}$ slots per pole per phase found in Example 5.2. The index numbers, therefore, are:
3 2 3 2 3 2 2 and the first 17 slots will have the coils arranged as
a a a c' c' b b b a a c' c' c' b b a a
- In the same way, if the whole number of the improper fraction of the number of slots per pole per phase is 3, then add 2 to the index numbers of similar fraction with the whole number 1. For example, if we want to find the index numbers for a winding having the number of slots per pole per phase $= 3\frac{2}{5}$, first we should find the index numbers for the winding having the number of slots per pole per phase $1\frac{2}{5}$ or $\frac{7}{5}$, and then add 2 to each other as follows:



The index numbers are 2 1 2 1 1, and for the winding with slots $3\frac{2}{5}$ per pole per phase the index numbers are 4 3 4 3 3.

The distribution of the conductors phasewise in the winding can then be shown from the index numbers.

For a winding with $1\frac{3}{7}$ slots per pole per phase, the coil span can be 9, 8 or 7 slots.

5.5 CHOICE OF ARMATURE WINDING

In general, for common types of three-phase induction motors, integral slot winding with chording or full pitch is used; the winding used is double-layer winding. For large synchronous generators, fractional slot windings are used. All are double-layer windings. A 60° phase spread is commonly used.

5.6 SINGLE-LAYER WINDING

Single-layer windings have only one coil side per slot and the number of armature coils is equal to one half the number of slots. The coils cannot have the same shape as the end connections lie in different planes. The number of conductors per slot may be odd or even.

Single-layer windings are of two types:

- (i) Unbifurcated in which coils comprising a pair of phase groups in adjacent pole pitches are concentric. The overhang is in two or three planes.
- (ii) Bifurcated windings in which each group is split into two sets of concentric coils, each set sharing its return coil sides with those of another group in the same phase. The overhang is in three planes.

Figure 5.4 shows a typical single-layer winding with 3 slots per pole per phase and a 60° phase spread. The winding is of the concentric type.

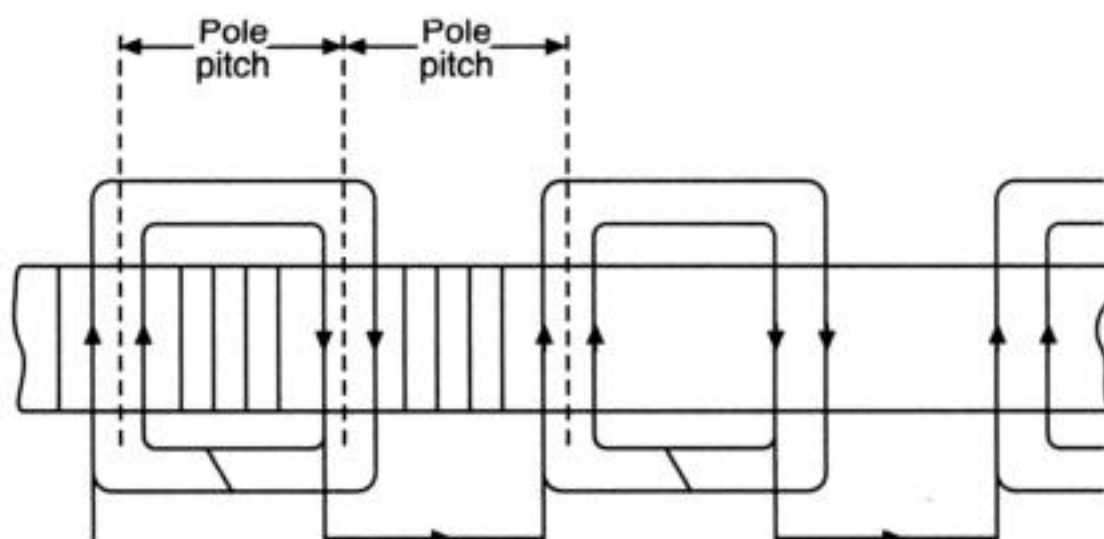


Figure 5.4 Single-layer concentric winding.

5.7 LAP WINDING

In dc machines, double-layer windings are used. In the simple lap winding, the connections are made from one commutator segment through the sides of the coil to the next commutator segment. Figures 5.5(a) and (b) show a single coil of a lap wound armature connected to commutator segments.

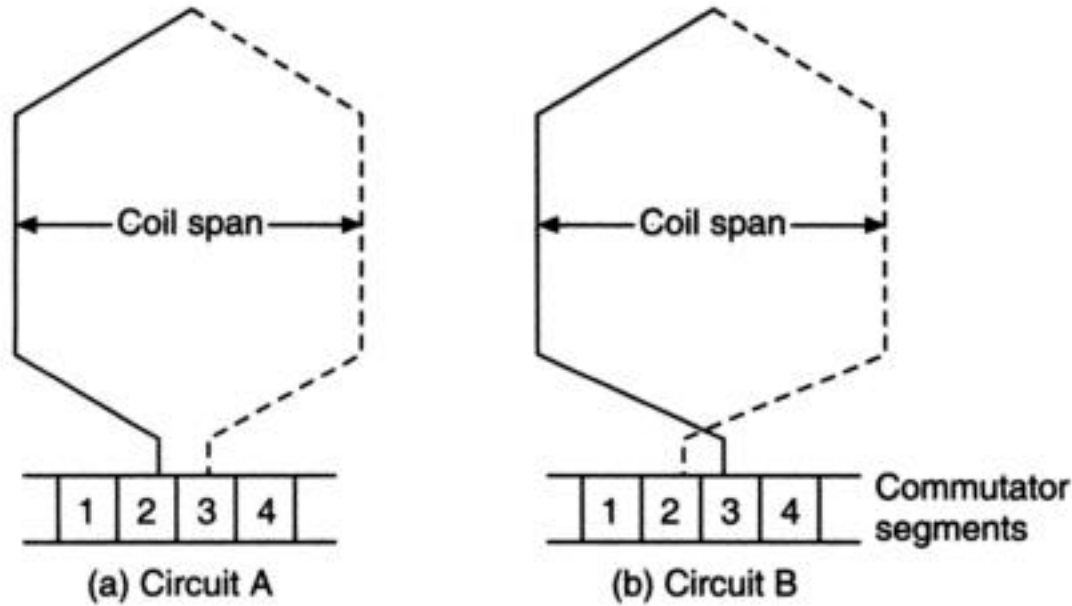


Figure 5.5 A single coil of armature with simple lap winding:
(a) progressive lap winding and (b) retrogressive lap winding.

The winding may be progressive or retrogressive.

The commutator pitch y_C for simple lap winding is given by

$$y_C = \pm 1 \quad (5.3)$$

For progressive winding $y_C = 1$; For retrogressive winding

$$y_C = -1$$

For the simple lap winding, the number of parallel paths in the armature circuit

$$a = p \quad (5.4)$$

The number of conductors in series per circuit

$$Z_c = \frac{Z_a}{p} \quad (5.5)$$

where Z_a is the total number of armature conductors.

$$\text{Number of coils} = \text{Number of commutator segments} \quad (5.6)$$

$$\text{Coil span} = \text{Pole pitch} = \frac{\text{Number of slots}}{p} \quad (5.7)$$

for the full-pitch winding.

The lap winding should satisfy the following conditions:

- (i) The pitch of the coil must be such that the opposite coil sides lie under unlike poles.
- (ii) The winding must include each coil side once only.
- (iii) The winding must be reentrant, i.e. it must close on itself.



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Multiplex wave winding

If multiplicity is m , then

$$\frac{p}{2} \times y_C = C \pm m \quad (5.16)$$

$$\text{The number of parallel paths } a = 2m \quad (5.17)$$

$$\text{Number of commutator segments } C = \frac{kp}{2} \pm m \quad (5.18)$$

where k is an integer.

The number of slots, the number of pole pairs $p/2$, and the number of commutator segments should be a multiple of m .

For symmetrical windings, equalizing connections may be used for multiplex wave windings as in the case of lap windings.

Voltage between adjacent commutator segments = (The voltage corresponding to simplex wave winding)/ m .

Dummy coils

In case the standard armature punchings are to be used which do not conform to the requirement of the simple wave winding, namely $(p/2)y_C = C \pm 1$, then more coils—usually one more—are placed in slots than those used. The extra coil is termed dummy coil. It is not connected to any armature segment. However, it is placed on the armature for mechanical balance.

EXAMPLE 5.6 Develop a simple wave winding for a 6-pole dc machine having 37 slots. The winding should be retrogressive. Show the winding table.

Solution:

Slots $S = 37$; the number of commutator segments $C = S = 37$ for the simple wave winding using single-turn coils or one coil side per layer; the number of poles $p = 6$.

The commutator pitch y_C is given by the relation $(p/2)y_C = C - 1$ as the winding has to be retrogressive.

Substituting the values, $3y_C = 37 - 1 = 36$ or $y_C = 12$

Pole pitch = $\frac{37}{6} = 6.166$. So take the coil span = 6 slots.

Starting with the commutator segment No. 1, the first coil side is placed in the top of the slot No. 1, and the second coil side of the same coil is placed at the bottom of slot No. 7 which is coil span apart and is denoted by 7'. The end of the coil is connected to commutator segment No. 13 which is y_C apart from the start connection of the coil to the commutator segment No. 1.

The winding is continued till it closes on the same commutator segment No. 1. Winding distribution of part of the winding is shown in the following winding Table 5.4.



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For lap winding, the number of commutator segments = $C = 67$

Number of poles = $p = 4$; Number of parallel paths = $a = 4$

$$\text{Current from the machine} = \frac{50 \times 100}{230} = 54.4 \text{ A}$$

$$\text{Current in each parallel path in lap winding} = \frac{217.4}{4} = 54.35 \text{ A}$$

The voltage of the generator = 230 V. The output will remain 50 kW with both types of winding.

If the winding is to be changed to wave winding, $a = 2$

$(p/2)y_C = C \pm 1$; for y_C to be a full number,

$$(p/2)y_C = 67 \pm 1 = 68 \text{ or } 66$$

$$y_C = \frac{68}{2} \text{ or } \frac{66}{2} = 34 \text{ or } 33. \text{ Choose } y_C = 33$$

When lap connected, the voltage between the commutator segments

$$= \frac{239}{67} \times 4 = 13.73 \text{ V}$$

In the case of wave connection, there are only 2 parallel paths.

The voltage across the brushes = $230 \times 2 = 460 \text{ V}$.

$$\text{Voltage between the adjacent commutator segments} = \frac{460}{67} \times 2 = 13.73 \text{ V}$$

$$\text{Current with a wave wound machine} = \frac{50 \times 1000}{460} = 108.7 \text{ A}$$

$$\text{Current in each parallel path} = \frac{108.7}{2} = 54.35 \text{ A}$$

Thus, it is seen that with lap wound connections, voltage = 230 V, and current = 217.4 A, while with the wave wound machine, voltage = 460 V, and current = 108.7 A. The output in both cases = 50 kW.

EXAMPLE 5.8 Find the possible two-circuit windings for a 4-pole dc machine. The conductors in series must be between 400 and 360, and the number of slots between 40 and 44. The number of commutator segments should be between 126 ± 4 .

Solution:

As it is a two-circuit winding, it is wave winding with $a = 2$; the number of poles $p = 4$. C is between 126 ± 4 . First find the possible commutator pitch y_C .

Alternatives are	$C \pm 1 = 126 \pm 1 = 127 \text{ or } 125$
or	$= 126 \pm 2 = 128 \text{ or } 124$
or	$= 126 \pm 3 = 129 \text{ or } 123$
or	$= 126 \pm 4 = 130 \text{ or } 122$

As the wave winding has to satisfy the relation

$$(p/2)y_C = C \pm 1; \text{ and } p = 4; C \pm 1 \text{ must be an even number.}$$

Therefore, out of the above alternatives,

$$C \pm 1 = 128 \text{ or } 124 \text{ giving } y_C = 64 \text{ or } 62$$

$$\text{or } C \pm 1 = 130 \text{ or } 122 \text{ giving } y_C = 65 \text{ or } 61$$

$$\text{In one case, } C = 2 \times 61 + 1 \text{ or } 2 \times 62 - 1 = 123$$

$$\text{In the second case, } C = 2 \times 64 + 1 \text{ or } 2 \times 65 - 1 = 129$$

Thus coils $C = 123$ or 129 . The number of slots = 41 or 43 using triple coil. The coil sides per slot = $3 \times 2 = 6$. Each commutator segment will have 6 conductors connected to it, i.e. total number of conductors = 123×6 or 129×6 , i.e. 738 or 774; therefore, conductors in series (two-circuit winding) = 369 or 387; thus they lie between 400 and 360, i.e. the limit given. The possible windings, therefore, are:

- (a) $C = 123$; $y_C = 61$ or 62 ; number of coil sides per slot = 6
- (b) $C = 129$; $y_C = 64$ or 65 ; number of coil sides per slot = 6

EXAMPLE 5.9 Find the nearest commutator segments and the suitable number of slots for an 8-pole, 4-circuit wave wound dc machine requiring about 720 conductors.

- (a) If coil sides per slot = 2
- (b) If coil sides per slot = 6

Solution:

- (a) About 720 conductors would be about 360 coils.

If $a = 4$, $m = 2$ and for wave winding, the following relation holds good:

$$(p/2)y_C = C \pm m$$

$(8/2)y_C = C \pm 2$. The commutator pitch y_C should be an integer. Therefore, $\frac{C \pm 2}{4}$ is an integer.

The number of coils or commutator segments divisible by 4 and nearest to 360, $(C \pm 2)$ is 360 or $C = 362$ or 358 .

Hence $C = \text{number of commutator segments} = S = \text{number of slots} = 362$ or 358 .

- (b) If six coil sides per slot are used,

$$C \pm 6 = 360 \text{ or } C = 366 \text{ or } 354$$

and the number of slots $S = 122$ or 118 as coil-sides per slot = 6 or coil-sides per coil = 3.

EXAMPLE 5.10 Select a two-circuit armature winding for a 4-pole, 1000 rpm 400 V dc machine. The flux per pole is about 0.04 Wb; armature stampings with 41, 45, and 51 slots are available

Solution:

$$\text{EMF induced} = \frac{\phi Znp}{60 \times a} \text{ V}$$

$$400 = \frac{0.04 \times Z \times 1000 \times 4}{60 \times 2}$$

$$Z = 300$$

With three alternative slots available, let us work out the commutator pitch.

$$(p/2)y_C = C \pm 1$$

$$(4/2)y_C = 51 \pm 1 \text{ or } y_C = 26 \text{ or } 25$$

$$(4/2)y_C = 45 \pm 1 \text{ or } y_C = 23 \text{ or } 22$$

$$(4/2)y_C = 41 \pm 1 \text{ or } y_C = 21 \text{ or } 20$$

$$Z_C = \text{number of conductors in series} = \frac{300}{2} = 150$$

The nearest choice is, therefore, $C = 51$.

Commutator segments = $C = 51$ coils.

Each coil will have 3 turns and the coil-sides per slot = 6;

$y_C = 26$ or 25 , i.e. progressive or retrogressive winding can be used.

$C = S = 51$; 3-turn coils; 6 coil sides per slot;

Total $Z = 51 \times 6 = 306$. This is near about 300 required to produce a flux of 0.04 weber in the air-gap of the machine for the given voltage to be induced.

It will be noted that the kW capacity of a machine is not affected if the flux per pole, number of poles, number of armature conductors and the speed at which the machine runs is kept the same. If the winding is changed, the number of parallel paths is changed which changes the current and the voltage at the terminals of the machine but not the kW capacity. Table 5.5 shows the effect for a 20 kW capacity machine with 6 poles wound in different ways.

Table 5.5 A 20 kw capacity machine with 6 poles wound in different ways

	<i>Paths</i>	Volts	Amps	kilowatts
Simplex lap	6	200	100	20
Duplex lap	12	100	200	20
Triplex lap	18	66.66	300	20
Simplex wave	2	600	33.33	20
Duplex wave	4	300	66.66	20
Triplex wave	6	200	100	20

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phase core type transformer,

$$2(a_1 T_1 + a_2 T_2) = k_w A_w$$

where k_w is the window space factor and A_w is the window area.

If δ is taken as current density, ampere-turns $I_1 T_1 = I_2 T_2 = (1/4)k_w A_w \delta$.

The rating or output of a three-phase transformer is given by

$$S = 3 V_1 I_1$$

$$S = 3 \times 4.44 \phi_m f T \times I \times 10^{-3} \text{ kVA}$$

Substituting the values, the expression for the output of a transformer comes out to be

$$S = 3.33 f A_i A_w B_m \delta k_w \times 10^{-3} \text{ kVA} \quad (6.2)$$

In the case of a single-phase transformer,

$$S = 2.22 f A_i A_w B_m \delta k_w \times 10^{-3} \text{ kVA} \quad (6.3)$$

6.3.1 Specific Magnetic Loading and Specific Electric Loading

The specific magnetic loading is the maximum flux density in the core, i.e. B_m . For power transformers, B_m is chosen between 1.5 and 1.7 Wb/m² using cold rolled steel. For distribution transformers, sometimes the lower flux density is used, i.e. 1.4 to 1.7 Wb/m².

The specific electric loading is the current density used. This depends on the type of cooling. For tanks with tubes and radiators $\delta = 2$ to 3 A/mm²; for forced cooling $\delta = 5$ to 6 A/mm².

6.4 DESIGN OF TRANSFORMERS

The design of transformers consists of designing the cross-section of the core, fixing up the frame size of the transformer core, design of windings, and design of tank. The criterion can be one of the following:

(a) Design the transformer for maximum efficiency or minimum total losses. The efficiency of transformer is maximum when the iron loss (or rather constant loss) is equal to the $I^2 R$ loss. If the transformer is to work on full load for most of the time, and the efficiency is to be maximum at this load, copper loss on full load is made equal to iron loss.

$$\frac{\text{Weight of iron}}{\text{Weight of copper}} = \frac{\text{Copper loss}}{\text{Iron loss}} \quad (6.4)$$

This equation gives the ratio of weights of active materials for the criterion of maximum efficiency at the mean working load.

(b) Another criterion for which the transformer can be designed is the minimum first cost of the transformer, i.e. make the cheapest transformer. Find the ratio of weight of iron to weight of copper for this condition.

(c) The third criterion for the design of transformer is on the basis of minimum annual cost, i.e. capital charge on cost of transformer + depreciation + cost of energy losses = minimum. This criterion needs a lot of information regarding the load curve of the system where the transformer is to be used, the cost of energy at different load factors, the load factor of the system, etc. in addition to the normal cost of transformer materials, etc. This is a complicated problem and can be solved only with the help of a computer.

The usual practice is to design a transformer for the best efficiency or the minimum losses. This is to be done consistent with the costs involved. The aim of the designer will be to keep the losses within the permissible limit given by the specifications.

6.5 DESIGN OF CORE

For design of the core, we use the relation,

$$\text{Voltage per turn } E_t = K\sqrt{S} \text{ V} \quad (6.5)$$

where S is the kVA output of transformer; K is constant that depends on the material and labour costs, etc. and on the type of transformer such as shell or core type and single-phase or three-phase. The approximate mean values for criterion of load for maximum efficiency are given in Table 6.3.

Table 6.3 Approximate mean values for criterion of load for maximum efficiency

Type	Single-phase	Three-phase power	Three-phase distribution
Core type	0.75 to 0.85	0.60 to 0.90	0.45 to 0.75
Shell type	1.00 to 1.20	1.00 to 1.50	0.80 to 1.25

The net cross-sectional area of the core can be determined by choosing K and then E_t and the flux density B_m .

Choosing B_m and δ , $A_i A_w$ is found from Eq. (6.3). The core design is done to conform to a standard frame. Figure 6.1 shows a frame giving the main dimensions of a three-phase core type transformer.

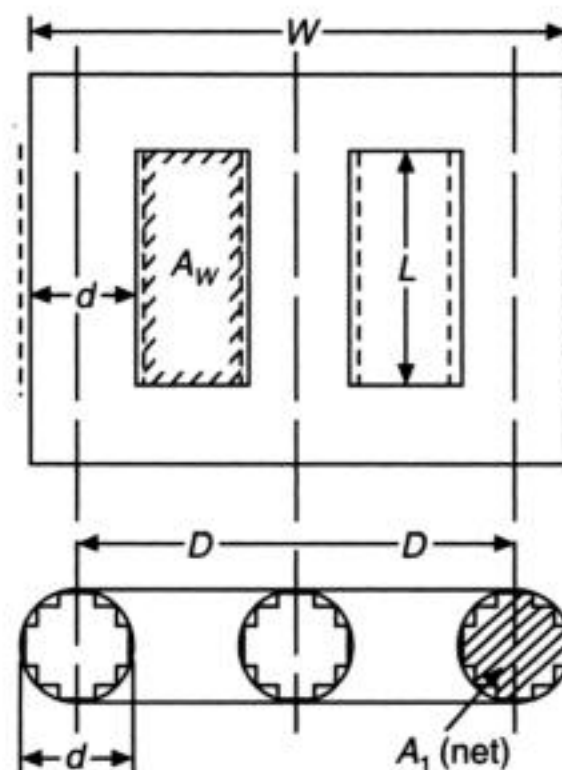


Figure 6.1 A standard frame for a three-phase core type transformer.

In Figure 6.1, d is the diameter of the core, D is the distance between the centres of the limbs, W is the width of the core frame, L is the length of the window, and A_w is the area of each window.

The core is built of 0.35 mm thin strips arranged in a number of steps so as to obtain nearly round cross-sectional area so that a better space factor for accommodating iron in the most useful way can be achieved.

The number of steps usually chosen is 3, 4, 5, 6, 7 or 9. For a larger size transformer, more steps may be used if this is found to be feasible. The area of the iron section in the steps in terms of the circumscribing diameter is given by

$$A_i = k k_s \frac{\pi D^2}{4} \text{ m}^2 \quad (6.6)$$

where k is the iron space factor given in the following Table 6.4.

Table 6.4 Iron space factor for typical number of steps in core

<i>Single-framed without ducts</i>	<i>Ducts</i>	<i>Core diameter (mm)</i>	<i>Number of steps</i>	<i>Iron space factor k</i>
	Nil	Less than 100	1	0.64
			2	0.79
			3	0.84
			4	0.87
		100–150	5	0.88
		250–300	6	0.89
Double frame	Longitudinal ducts	350–750	6–8	0.86
	Longitudinal and cross ducts	550–1000	7–10	0.88

This is due to there being steps instead of one solid round section of the core. k_s = stacking factor due to paper or varnish insulation between the laminations of the core. This may be taken as approximately 0.92.

Figures 6.2(a) and (b) show the typical sections of 3-step and 6-step cores with the approximate widths of the lamination pieces used.

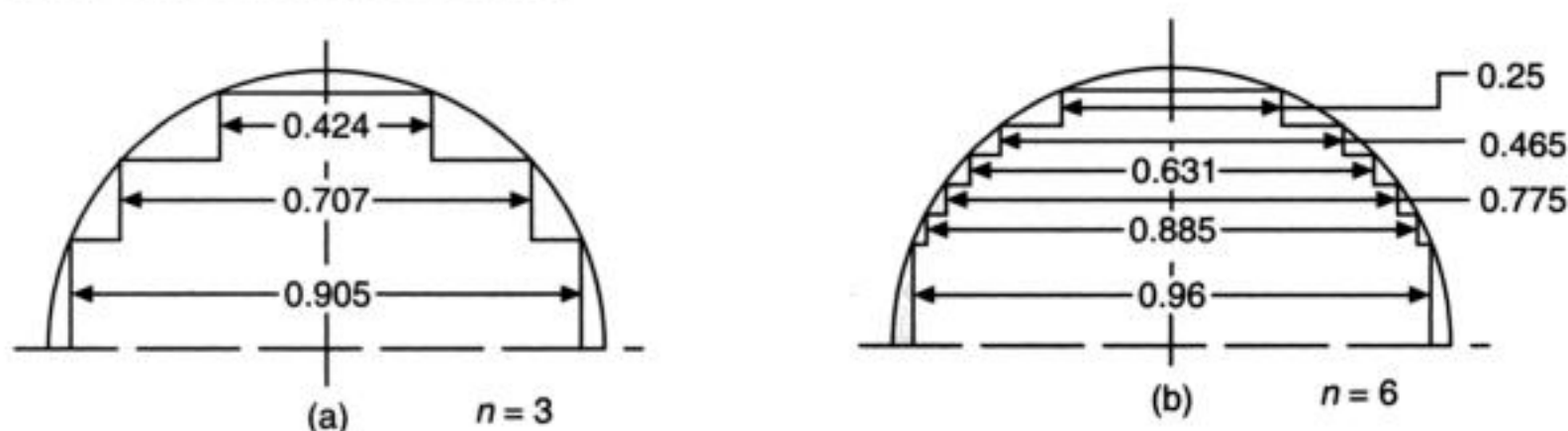


Figure 6.2 (a) 3-steps core section and (b) 6-steps core section.

6.6 DESIGN OF WINDINGS—MAIN DIMENSIONS OF FRAME

We know that the expression for the output of a three-phase transformer is given by

$$S = 3.33 A_i A_w k_w \delta B_m f \times 10^{-3} \text{ kVA} \quad (6.3)$$



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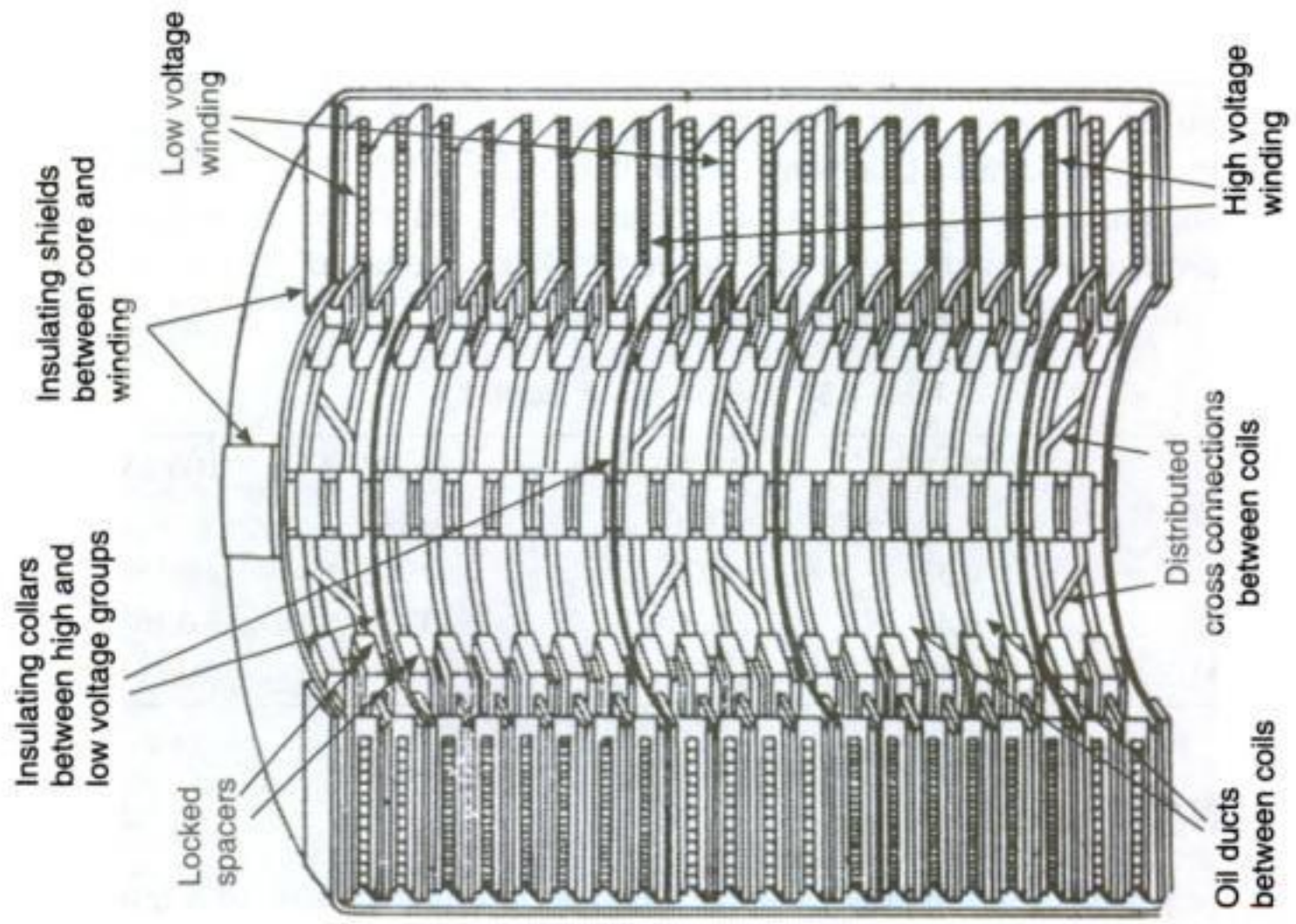


Figure 6.4 Interleaved type winding with disc type H.V. and L.V. coils.

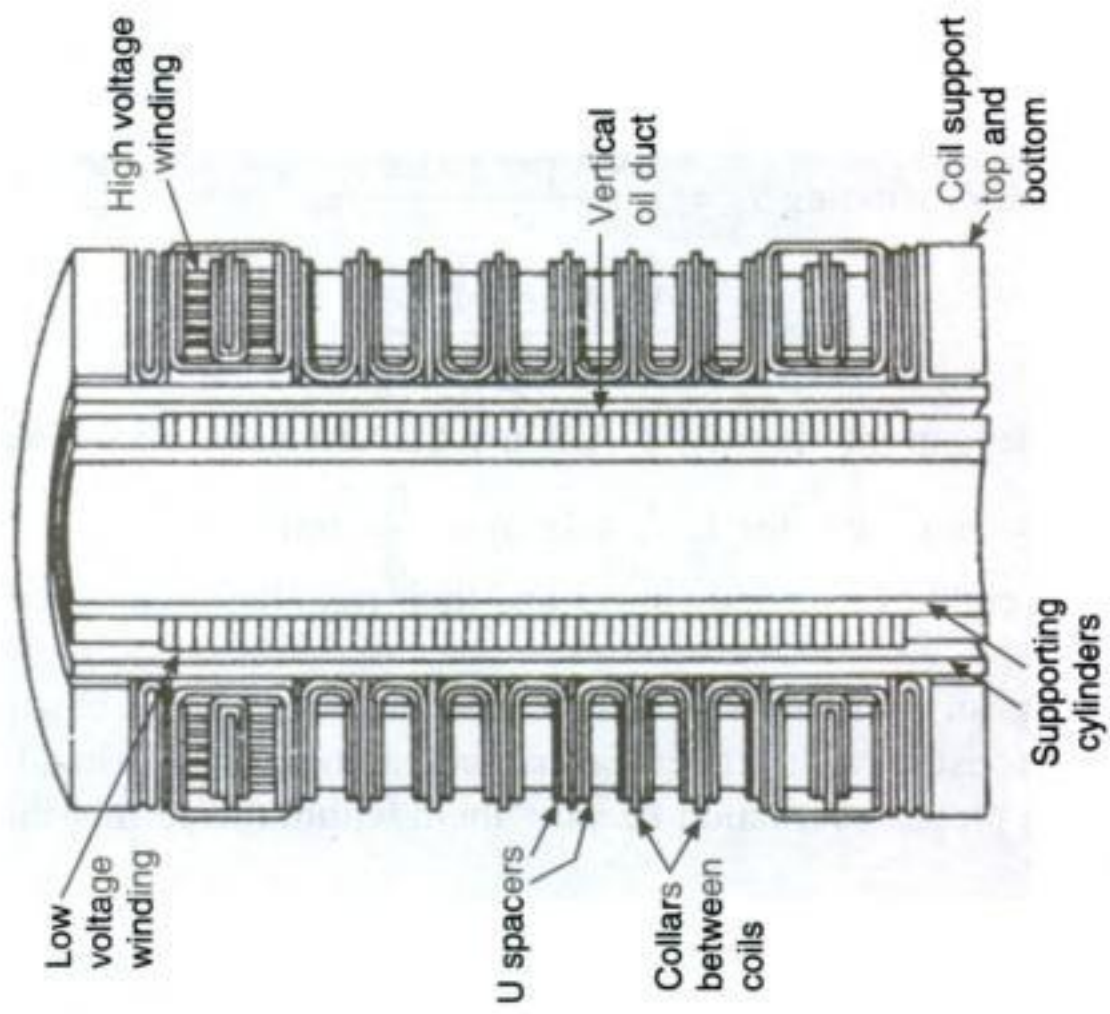


Figure 6.3 Concentric type winding with disc type H.V. coils.



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15. Design the low voltage winding:
 - Number of turns per phase
 - Number of turns per layer
 - Number of layers; size of conductor
 - Inside diameter of the coil; outside diameter of the coil
 - Thickness of the coil; mean diameter of the coil
 - Mean length of the turn
 - Height of the coil in window.
16. Design the high voltage winding:
 - Number of turns per phase
 - Number of coils
 - Number of turns per coil
 - Size of conductor
 - Inside diameter of the coil; outside diameter of the coil
 - Thickness of the coil; mean diameter of the coil
 - Mean length of turn
 - Height of coils in window
- 16A. Calculate the % reactance.
17. Calculate the % resistance.
18. Calculate the % impedance.
19. Find the weight of the iron in core and yoke.
20. Find the core or iron loss.
21. Find the magnetizing VA.
22. Find the weight of L.V. winding.
23. Calculate the resistance of L.V. winding.
24. Find the weight of H.V. winding.
25. Find the weight of copper in transformer.
26. Calculate the resistance of H.V. winding.
27. Find the turns ratio of H.V./L.V., i.e. T_1/T_2 .
28. Calculate the equivalent resistance referred to H.V.
29. Calculate the copper loss $3I^2r$ allowing 7% to 10% for stray load loss; find the load loss at 75°C.

Calculation of performance

30. Calculate the efficiency on full load, 3/4th load and 1/2 load at unity p.f. (and at 0.8 p.f. lagging if required).
31. Calculate the regulation at unity p.f. and 0.8 p.f. lagging.
32. Calculate the core loss current, the magnetizing current and the no-load current.

Design of tank

33. Choose the inner dimensions of the tank to accommodate transformer with necessary clearances.

34. Find the volume and weight of oil required. Find the temperature rise.
35. Find the number of radiator or tubes required as extension of the cooling surface so as to be within the required temperature limits.
36. Find the weight of transformer (and radiators if any).
37. Find the total weight of transformer.

Summary

38. Specifications.
39. Dimensions of core assembly, coils, tank.
40. Performance of transformer: efficiency, regulation, no load current, % impedance.
41. Diagram of connections.

6.14 DESIGN OF DISTRIBUTION TRANSFORMERS

The distribution transformers are designed and built either by the use of copper conductors or aluminium conductors. The procedure and calculations for the design of distribution transformers of 100 kVA and 63 kVA size are illustrated by the following examples. The detailed specifications are given, the designs worked out and the performance calculations are done.

EXAMPLE 6.1 Design a 100 kVA, three-phase, 50 Hz, 11000/433 V, delta/star distribution transformer. Tappings $\pm 2.5\%$, $\pm 5\%$ on high voltage side. Cooling ON (self oil-cooled). Temperature rise over oil 50°C . No-load loss 355 W; copper and stray load loss not more than 2000 W. Percentage impedance 4.5%.

Calculate the no-load current, efficiency at 75°C on full load, 75% load and 50% load at unity power factor; regulation on full load at 75°C at unity power factor and at 0.8 power factor lagging.

Solution:

Voltage per turn E_t : An empirical expression which gives voltage per turn fairly accurately for transformers is

$$E_t = \frac{\sqrt{\frac{\text{kVA} \times 1000}{\text{No. of legs}}}}{40}; \text{ for three-phase core type transformers, the number of legs} = 3$$

$$E_t = \frac{1}{40} \sqrt{\frac{100 \times 1000}{3}} = 4.56, \text{ Choose } E_t = 4.5 \text{ V/turn.}$$

Specific magnetic loading:

Choose $B_{\max} = 1.7 \text{ Wb/m}^2$; material for core is chosen as cold rolled grain oriented (CRGO) steel laminations of 0.35 mm thickness; Mitred core construction is used; Mitred at 45° .

Cross-section of the core:

$$E_t = 4.44 B_m f A_i \text{ volts}$$

where B_m = flux density in Wb/m²

$$f = 50 \text{ Hz}$$

A_i = net cross-sectional area of the core in m².

$$A_i = \frac{4.5 \times 10^6}{4.44 \times 1.7 \times 50} = 11,923 \text{ mm}^2$$

Diameter of the circumscribing circle for the core, d :

Choose a 7-step core. The area should be nearly circular. In the case of a 7-step core, the core space factor = 0.88 and the stacking factor for laminations = 0.92. Hence if d = diameter of the core section,

$$A_i = 0.88 \times 0.92 \times \frac{\pi d^2}{4}$$

$$d^2 = \frac{11933 \times 4}{0.88 \times 0.92 \times \pi} = 18752 \text{ mm}^2 \quad \text{and} \quad d = 136.93 \text{ mm}$$

Choose $d = 140 \text{ mm}$

then $\text{Area } A_i = \frac{\pi d^2}{4} \times 0.88 \times 0.92 = 12,463 \text{ mm}^2$

With this area, check B_m .

$$E = 4.44 \times B_m \times 50 \times 12463 \times 10^{-6} = 4.5 \quad \text{from which } B_m = 1.63 \text{ Wb/m}^2$$

Window area A_w :

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

Window space factor k_w is taken approximately as 0.29.

A_w = window area; δ = current density taken as 2.5 A/mm²; S = output in kVA

$$A_w = \frac{100 \times 10^6 \times 10^3}{3.33 \times 12463 \times 0.29 \times 2.5 \times 1.63 \times 50} \text{ mm}^2 = 40,779 \text{ mm}^2$$

Choose window width = 150 mm (about d); Then the height of the window

$$= \frac{40,779}{150} = 272 \text{ mm. Choose height of}$$

the window = 2 × width of window approx. = 150 × 2 = 300 mm checking clearance to yoke. This is later taken as 334 mm.

Then window area = 300 × 150 = 45,000 mm²

The main dimensions of the core are therefore: diameter $d = 140 \text{ mm}$; D = distance between the centres of the

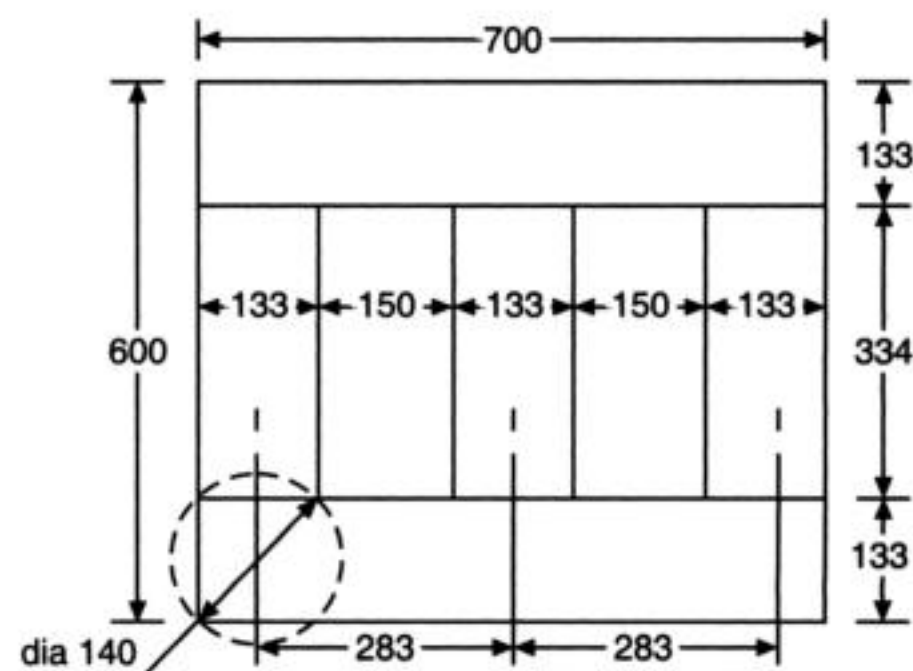


Figure 6.8 Core and assembly dimensions for Example 6.1.

adjacent limbs = $150 + 133 = 283$ mm; with a 7-step core, the largest width of the core with $d = 140$ mm is $0.95 \times 140 = 133$ mm. Figure 6.8 shows the core and yoke assembly dimensions.

Height of window = 334 mm. Total width = $(2 \times 283) + 133 = 699$ mm ≈ 700 mm

Total height = $334 + 133 + 133 = 600$ mm

Check the window space factor approximately before fixing the core and window dimensions.

Number of turns in L.V. winding:

Voltage per phase = $433/\sqrt{3} = 250.3$ V as the winding is star-connected. Turns per phase on L.V.

winding = $\frac{250.3}{4.5} = 55.62$. Choose 56 turns.

Number of turns on H.V. winding:

Turns per phase on H.V. winding = $\frac{11000}{4.5} = 2444$ as the winding is delta connected; Tappings

of $\pm 5\%$ and $\pm 2.5\%$ are to be provided on the H.V. winding.

Turns on H.V. winding for normal connections = 2444

5% more, $2444 \times 1.05 = 2566$; 2.5% more, $2444 \times 1.025 = 2505$

5% less, $2444 \times 0.95 = 2322$; 2.5% less, $2444 \times 0.975 = 2383$.

Thus the turns for H.V. winding are:

2566	2505	2444	2383	2322
5%	2.5%	normal	-2.5%	-5%

tappings.

Low voltage winding: Current per phase = $\frac{100 \times 1000}{\sqrt{3} \times 433} = 133.5$ A

Choose helical cylindrical coil.

Current density δ assumed = 2.5 A/mm²

Area of L.V. conductor $a_2 = \frac{133.5}{2.5} = 53.4$ mm²

Choose a rectangular copper conductor from IS:6160:1977 for rectangular copper conductors for electrical machines, giving an area near about the required one.

Choose a section 4.5 mm thickness $\times$ 6.3 mm width; 2 conductor strips forming the conductor of L.V. area $a_2 = 27.49 \times 2 \approx 55$ mm².

High voltage winding: Choose disc coils.

Current in H.V. winding per phase = $\frac{100 \times 1000}{3 \times 11000} = 3.03$ A being delta connected.

Cross-section of conductor for H.V. winding:

$a_1 = \frac{3.03}{2.5} = 1.212$ mm². Choose a round conductor

$a_1 = \frac{\pi d^2}{4} = 1.212$ where d = diameter of the conductor in mm.

$d^2 = 1.54$ or $d = 1.212$ mm. Choose diameter of the conductor = 1.25 mm.

Then area = $\frac{\pi}{4} \times 1.25^2 = 1.23 \text{ mm}^2$.

Copper area in window = $2(a_1 T_1 + a_2 T_2) = 2(55 \times 56 + 1.23 \times 2566)$
 $= 2 \times 6236 \text{ mm}^2$

Window space factor $k_w = \frac{6236 \times 2}{45000} = 0.277$ which is near about 0.29 chosen.

The next test for finalisation of the window area and the final dimensions of core and yoke assembly is to choose the layout of the L.V. and H.V. windings with the correct required clearances and insulation between parts of L.V. and H.V. windings and core and tank and check whether the windings can be conveniently accommodated in the window area.

Also check the % reactance X before further calculations.

Design and layout of L.V. winding:

Number of turns 56. Size of conductor : 2 strips of 6.3×4.5 mm copper rectangular conductors. With paper insulation for conductors, the size of each conductor will be $(6.3 + 0.25)$ mm $\times$ $(4.5 + 0.25)$ mm; choose 2 layers for L.V. winding, turns per layer = $56/2 = 28$. Conductor layout is shown in Figure 6.9. Width of conductor 6.55 mm is taken along the winding with 2 conductor sides $4.75 + 4.75$ or 9.5 mm forming the conductor per layer. For two layers, the dimension of conductors width-wise is 19 mm and height of window-wise 6.55 mm for each conductor.

Height of L.V. winding in window = $28 \times 6.55 = 183.4$ mm say 184 mm;

Thickness of L.V. coil = $9.5 \times 2 = 19$ mm

Distance between core and L.V. coil = 3.5 mm

Inside diameter of L.V. coil = $140 + (2 \times 3.5) = 147$ mm

Outside diameter of L.V. winding = $147 + (2 \times 19) = 185$ mm

Mean diameter of L.V. coil = $147 + 19 = 166$ mm

Mean length of turn of L.V. coil = $\pi \times 166 = 521.5$ mm

Design and layout of H.V. winding:

Layout of H.V. winding is shown in Figure 6.10.

The distance between L.V. and H.V. = 12 mm

Inside diameter of H.V. = $185 + (12 \times 2) = 209$ mm

Split H.V. winding in 4 coils each with turns = $2566/4 = 642$

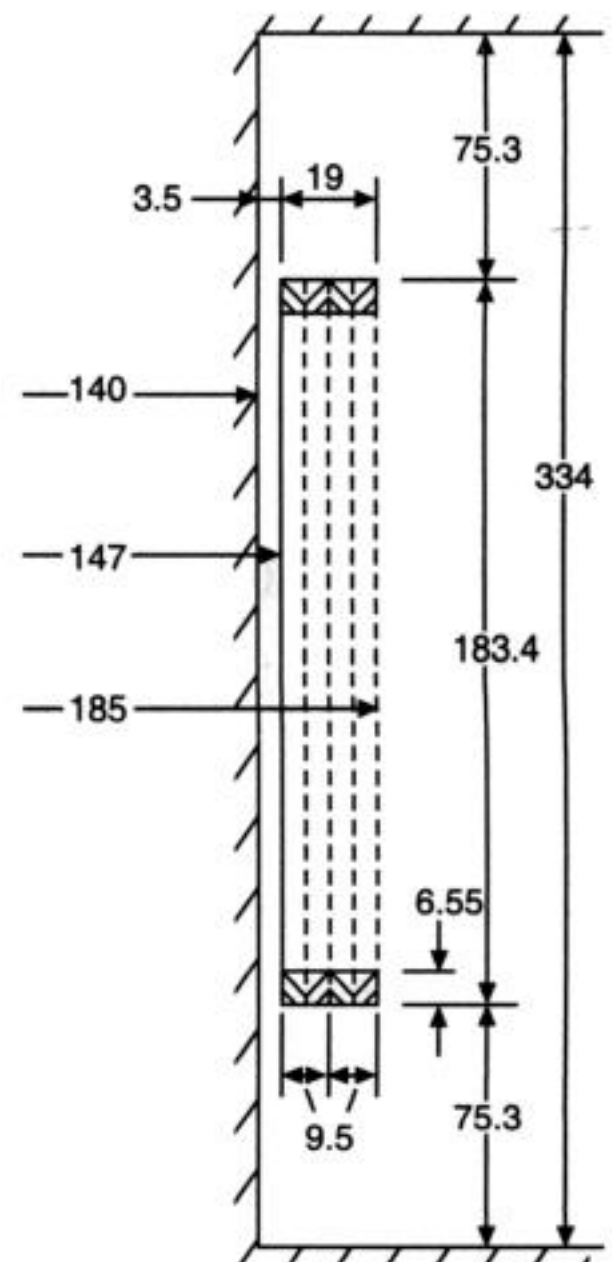


Figure 6.9 Layout of L.V. winding (all dimensions in mm).



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$$\text{Average } L_{mt} = \frac{521.5 + 727.3}{2} = \frac{1248.8}{2} = 624.4 \text{ mm}$$

$$AT = 133.5 \times 56$$

$$\text{Mean height of coils} = \frac{184 + 282}{2} = 233 \text{ mm}$$

$$a = 12 \text{ mm}; b_1 = \text{width of H.V.} = 22.5 \text{ mm}; b_2 = \text{width of L.V.} = 19 \text{ mm}$$

$$a + \frac{b_1 + b_2}{3} = 12 + \frac{22.5 + 19}{3} = 25.8 \text{ mm}$$

$$\% \text{ reactance } X = \frac{2\pi \times 50 \times 4\pi \times 10^{-7} \times 0.6244 \times 133.5 \times 56 \times 0.0258}{0.233 \times 4.5}$$

$$X = 0.0453 \text{ p.u. or } 4.53\%$$

Percentage resistance:

Resistance of low voltage winding: (per phase)

$$\rho_{20} = 0.01724 \text{ } \Omega/\text{mm}^2/\text{m}; \quad \alpha_{20} = 0.00393$$

$$\begin{aligned} \text{At } 75^\circ\text{C, } \rho_{75} &= \rho_{20}\{1 + \alpha_{20}(75 - 20)\} \\ &= 0.01724 \times (1 + 0.00393 \times 55) \\ &= 0.021 \text{ } \Omega/\text{mm}^2/\text{m} \end{aligned}$$

$$\text{Resistance of L.V. winding} = \frac{0.021 \times 521.5 \times 56}{55 \times 1000} = 0.0111 \text{ } \Omega$$

$$\text{Resistance of H.V. winding (per phase)} = \frac{0.021 \times 727.3 \times 2444}{1.23 \times 1000} \text{ } \Omega = 30.34 \text{ } \Omega$$

$$\text{Ratio of transformation} = \frac{T_1}{T_2} = \frac{11000}{250.3} = 43.95$$

Equivalent resistance referred to H.V. winding (per phase)

$$R = 30.34 + 0.0111 \times 43.95^2 = 30.34 + 21.44 = 51.78 \text{ } \Omega$$

$$\text{Percentage resistance: } \frac{3.03 \times 51.78}{11000} \times 100\% = 1.42\% \text{ or } 0.0142 \text{ p.u.}$$

Percentage impedance: % X = 4.53%; % R = 1.42%

$$\% Z = \sqrt{(4.53^2 + 1.42^2)} = \sqrt{22.53} = 4.74\%$$

Weight of iron in core and yoke assembly:

From Figure 6.8, the volume of the core and yoke is given by

$$A_i\{700 \times 2 + 334 \times 3\} = 2402 \times 12463 \text{ mm}^3$$

Weight of iron = $7.85 \times 1000 \text{ kg/m}^3$.

$$\text{Weight of core and yoke} = \frac{12463 \times 2402 \times 7.85}{1000 \times 1000} = 235 \text{ kg}$$

Core loss at $B_{\max} = 1.63 \text{ Wb/m}^2$ is 1.3 W/kg

Core loss in transformer $235 \times 1.3 = 306 \text{ W}$

Magnetizing volt-amperes:

For $B_{\max} = 1.63 \text{ Wb/m}^2$, VA/kg from the curve is 10 VA/kg

Magnetizing volt-amperes = $235 \times 10 = 2350 \text{ VA}$

Weight of L.V. winding: density of copper 8.89 g/cm^3

Number of turns = 56; $a_2 = 55 \text{ mm}^2$;

Mean length of turn = 521.5 mm ;

$$\text{Weight of L.V. winding (per limb)} = \frac{8.89 \times 55 \times 521.5 \times 56}{1000 \times 1000} = 14.28 \text{ kg}$$

Weight of H.V. winding (per limb):

Number of turns = 2566; normal 2444; $a_1 = 1.23 \text{ mm}^2$; mean length of turn = 727.3 mm

Weight of four coils (one limb):

Number of turns = 2566; normal 2444; $a_1 = 1.23 \text{ mm}^2$; mean length of turn = 727.3 mm

$$\begin{aligned} \text{Weight of four coils (one limb)} &= \frac{8.89 \times 1.23 \times 727.3 \times 2566}{1000 \times 1000} \text{ kg} \\ &= 20.40 \text{ kg for all turns} \end{aligned}$$

For normal turns,

$$\text{Weight of the coils (one limb)} = \frac{8.89 \times 1.23 \times 727.3 \times 2444}{1000 \times 1000} = 19.44 \text{ kg}$$

Total weight of copper in transformer:

$$3(\text{L.V.} + \text{H.V.}) = 3(14.28 + 19.44) = 3 \times 33.72 \text{ kg} = 101.16 \text{ kg}$$

Copper loss and load loss at 75°C :

H.V. current per phase = 3.03 A

Copper loss for 3-phases = $3 \times I^2 \times r = 3 \times 3.03^2 \times 51.78 = 1426 \text{ W}$

Add stray load loss about 7%, then load loss at 75°C

$$= 1426 \times 1.07 = 1526 \text{ W}$$

Iron loss = 306 W ; total loss = $306 + 1526 = 1832 \text{ W}$.

Calculation of performance:

Efficiency on full load at unity power factor:

Output = $100 \times 1000 \text{ W}$;

$$\text{Efficiency} = \frac{100 \times 1000 \times 100}{100 \times 1000 + 1832} = 98.2\%$$

Efficiency on 3/4th full load at unity power factor:

$$\text{Core loss} = 306 \text{ W; load loss on } 3/4\text{th load} = 1526 \times (3/4)^2 = 858 \text{ W}$$

$$\text{Total loss} = 306 + 858 = 1164 \text{ W}$$

$$\text{Efficiency on } 3/4\text{th load} = \frac{0.75 \times 100 \times 100}{75000 + 1164} \times 100\% = 98.4\%$$

Efficiency on 1/2 full load at unity power factor:

$$\text{Core loss} = 306 \text{ W; load loss on } 1/2 \text{ load} = 1526 \times 1/4 = 373 \text{ W}$$

$$\text{Total loss} = 306 + 381 = 687 \text{ W}$$

$$\text{Efficiency on } 1/2 \text{ of full load} = \frac{50,000}{50,000 + 687} \times 100\% = 98.6\%$$

Regulation on full load at unity power factor:

$$\% R = 1.42\%, \% X = 4.53\%$$

$$(V + IR)^2 + (IX)^2 = E^2$$

$$(1.0 + 0.0142)^2 + (0.0453)^2 = 1.0306 \text{ or } E = 1.015$$

$$\text{Regulation} = 1.015 - 1.0 = 0.015 \text{ p.u. or } 1.5\%$$

Regulation on full load at 0.8 power factor lagging:

$$= IR \cos \phi + IX \sin \phi = 1.42 \times 0.8 + 4.53 \times 0.6$$

$$= 1.136 + 2.718 = 3.854\%$$

Core loss current, magnetizing current, no-load current:

$$\text{Core loss} = 306 \text{ W}$$

$$\text{Core loss current } I_c = \frac{306}{3 \times 11000} = 0.0093 \text{ A}$$

$$\text{Magnetizing VA} = 2350; \text{ magnetizing current } I_m = \frac{2350}{3 \times 11000} = 0.071 \text{ A}$$

$$\text{No-load current per phase} = I_0 = \sqrt{(0.071^2 + 0.0093^2)} = 0.0716 \text{ A}$$

$$\text{Current per phase} = 3.03 \text{ A}$$

$$\text{No-load current} = \frac{0.0716}{3.03} \times 100\% = 2.36\% \text{ of full load current}$$

Design of tank:

Figure 6.11 shows the spacing of outside diameters of H.V. coils on the cores. Outside diameter of H.V. = 254 mm; the distance between coils on adjacent limbs = 29 mm; clearance at each end is 40 mm. Thus the length of the tank = $254 \times 3 + 29 \times 2 + 2 \times 40 = 900$ mm; breadth of the tank = 254 plus 60 mm on either side to accommodate tapplings and leads to be taken out. Thus, breadth = $254 + (60 \times 2) = 374$; choose 375 mm; height = 600 + 50 for base + 250 oil level above core = 900 mm up to oil level; plus 250 mm for leads, etc. = 1150 mm.

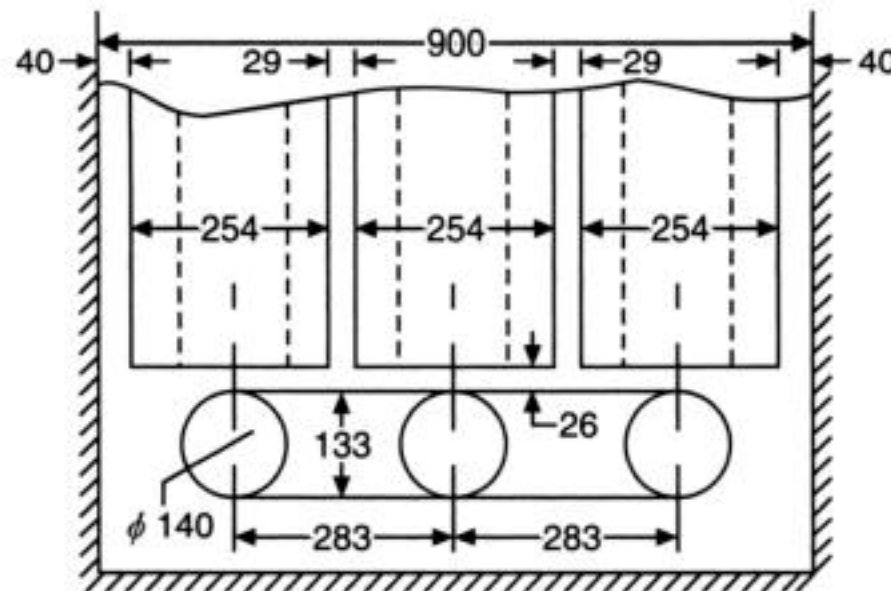


Figure 6.11 Tank dimensions (Example 6.1, with all dimensions in mm).

Inside dimensions of the tank of the transformer

$$= 900 \times 375 \times 1150 \text{ mm (length} \times \text{breadth} \times \text{height)}$$

Temperature rise:

For dissipation of heat, only four surfaces of a tank are taken into consideration. The top and the bottom are not considered.

$$\text{Surface of tank} = \frac{1150}{1000} \times \frac{375}{1000} \times 2 = 0.8625 \text{ m}^2$$

$$\frac{1150}{1000} \times \frac{900}{1000} \times 2 = 2.07 \text{ m}^2$$

$$\text{Total} = 2.9325 \text{ m}^2$$

Full-load loss to be dissipated = 1832 W

If 12.5 watts per m² per °C temperature rise is taken as dissipation due to convection and radiation, the temperature rise

$$= \frac{1832}{12.5 \times 2.9325} = 50^\circ \text{C}$$

The temperature of transformer walls may be limited to 35°C.

Then the temperature rise of the oil will be 50°C and of coils 55°C.

In that case the surface of the tank for cooling has to be increased either by radiators or by tubes attached to the tank.

If the total surface area is considered x times the tank surface area, then

$$2.9325x \left(8.8 + \frac{3.7}{x} \right) 35 = 1832 \text{ from which } x = 1.61.$$

Thus the additional area to be provided = $2.9325 \times 0.61 = 1.79 \text{ m}^2$

900 mm is height up to oil level; height of tube is taken as 850 mm

Surface of 1 tube of 50 mm diameter = $\pi \times 50 \times 850 \times 10^{-6} = 0.1335 \text{ m}^2$

$$\text{Number of tubes required} = \frac{1.79}{0.1335} = 13.4 \text{ say } 14$$

Volume and weight of oil:

$$\text{Volume of tank up to oil level of 900 mm} = \frac{900}{1000} \times \frac{375}{1000} \times \frac{900}{1000} = 0.303 \text{ m}^3$$

$$\begin{aligned} \text{Volume of transformer core and copper} &= \frac{98.7}{8.89 \times 10000} + \frac{235}{7.85 \times 1000} \\ &= 0.011 + 0.03 = 0.0411 \text{ cu}^3 \end{aligned}$$

$$\begin{aligned} \text{Volume of oil} &= \text{Volume of tank up to oil level} - \text{Volume of core and windings} \\ &= 0.303 - 0.0411 = 0.2619 \text{ m}^3 \end{aligned}$$

$$\text{Oil required in transformer} = 0.2619 \times 1000 \text{ litres} = 261.9 \text{ litres say } 262 \text{ litres.}$$

$$\text{Weight of oil required} = 262 \times 0.89 = 233 \text{ kg}$$

Weight of tank:

If the thickness of the tank walls is taken as 5 mm,

$$\begin{aligned} \text{Weight of tank} &= 0.005 \left(\frac{1150}{1000} \times \frac{375}{1000} \times 2 + \frac{1150}{1000} \times \frac{900}{1000} \times 2 + \frac{900}{1000} \times \frac{375}{1000} \times 2 \right) \\ &\quad \times 1000 \times 7.15 = 141.3 \text{ kg} \end{aligned}$$

Volume and weight of oil in tubes:

14 tubes each of 50 mm diameter and 0.85 m length.

$$\text{Volume} = \frac{\pi}{4} \left(\frac{50}{1000} \right)^2 \times 0.85 \times 14 = 0.0233 \text{ m}^3$$

$$\text{Volume of oil in tubes} = 0.0233 \times 1000 = 23.3 \text{ litres}$$

$$\text{Weight of oil in tubes} = 23.3 \times 0.89 = 20.73 \text{ kg}$$

$$\text{Weight of tubes} = \pi D l \times 0.005 \times 14 \times 7.85 \times 1000 \text{ kg}$$

$$\begin{aligned} &= \pi \times \frac{50}{1000} \times 0.85 \times 0.005 \times 14 \times 7.85 \times 1000 \\ &= 73 \text{ kg} \end{aligned}$$

Total weight of transformer:

Weight of core and yoke assembly	235 kg
Weight of copper in windings	101.16 kg
Weight of tank and tubes	141.3 kg
	73.0 kg
Weight of oil in tank and tubes	233 kg
	30.73 kg
Total weight	804.19 kg
Say	805 kg



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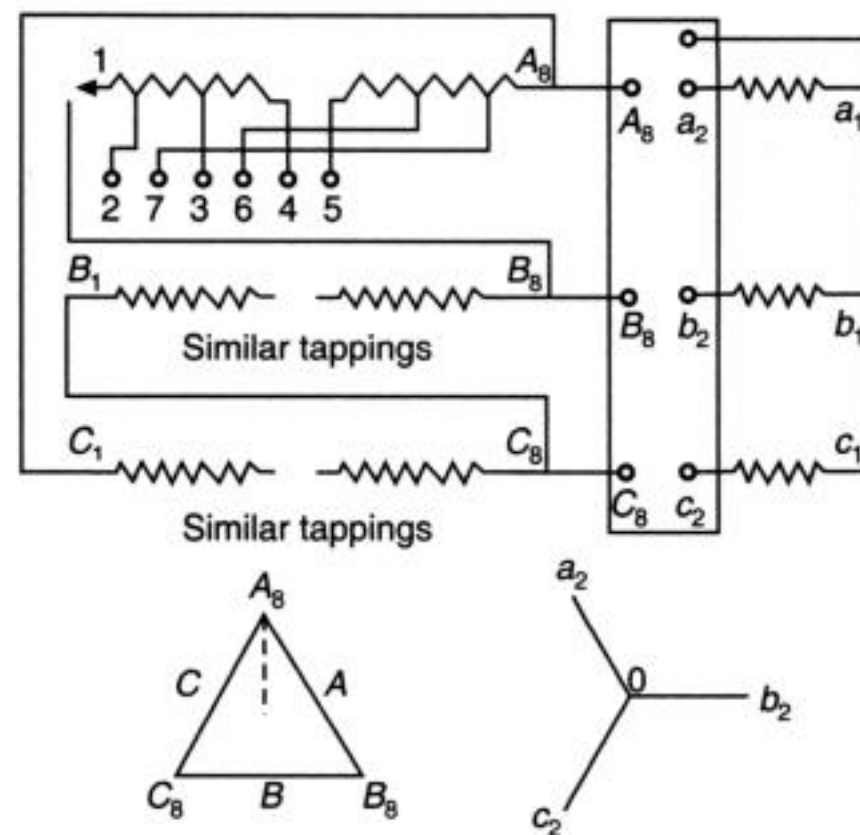


Figure 6.12 Diagram of connections, tapplings, vector group, connections for different voltages on H.V. side.

Table 6.6 Properties of copper and aluminium conductors

Characteristic	Annealed copper	Annealed aluminium
Volume resistivity at 20°C ($\Omega/\text{mm}^2/\text{mm}$)	0.017241	0.0280
Volume conductivity %	100	61
Temperature coefficient of resistance at 20°C/°C	0.00393	0.00403
Density at 20°C (g/cm^3)	8.89	2.703
Weight ($\text{kg}/\text{mm}^2/\text{km}$)	8.89	2.703
Thermal conductivity ($\text{W}/\text{m}^3/^\circ\text{C}$)	350	200

A sample design of an aluminium transformer is worked out below:

EXAMPLE 6.2 Design a 63 kVA, three-phase, 50 Hz, 11000/433 V, delta–star distribution transformer for rural electrification. No tapplings are used. Cooling ON; temperature rise: 50°C oil temperature rise; total loss not more than 1660 watts, load loss at 75°C not to exceed 1400 W. No load loss 260 W, percentage impedance 4.5%.

Find the no-load current, efficiency on full load, 3/4th full load, and 1/2 full load at unity power factor; find regulation on full load at unity power factor and 0.8 power factor lagging.

Solution:

Volts per turn:

$$E_t = \frac{1}{40} \sqrt{\left(\frac{\text{kVA} \times 100}{\text{Number of legs}} \right)} = \frac{1}{40} \sqrt{\left(\frac{63000}{3} \right)} = 3.62$$

For aluminium transformers, choose E_t less than this value, say 3.4. Choose $B_{\text{max}} = 1.7 \text{ Wb}/\text{m}^2$; choose a 7-step core; CRGO mitred core construction 45° cut.

$$E_t = 4.44 B_m f A_i$$

$$A_i = \frac{3.4 \times 10^6}{4.44 \times 1.7 \times 50} = 9009 \text{ mm}^2$$

$$= 0.88 \times 0.92 \times \frac{\pi d^2}{4}$$

from which $d^2 = 14168 \text{ mm}^2$ and $d = 119 \text{ mm}$. Take $d = 120 \text{ mm}$

Then
$$A_i = 0.88 \times 0.92 \times \frac{\pi \times 120^2}{4} = 9192 \text{ mm}^2$$

Width of the longest core section side = $120 \times 0.92 = 110 \text{ mm}$ approximately.

Window area:

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

$$63 = 3.33 \times \frac{9192}{10^6} \times A_w \times 0.29 \times 1.5 \times 1.7 \times 50 \times 10^{-3}$$

from which $A_w = 55664 \text{ mm}^2$.

Choose window width = 150 mm and window height = 350 mm

Window area = $350 \times 150 = 52.500 \text{ mm}^2$. The size of the window and core chosen is shown in Figure 6.13.

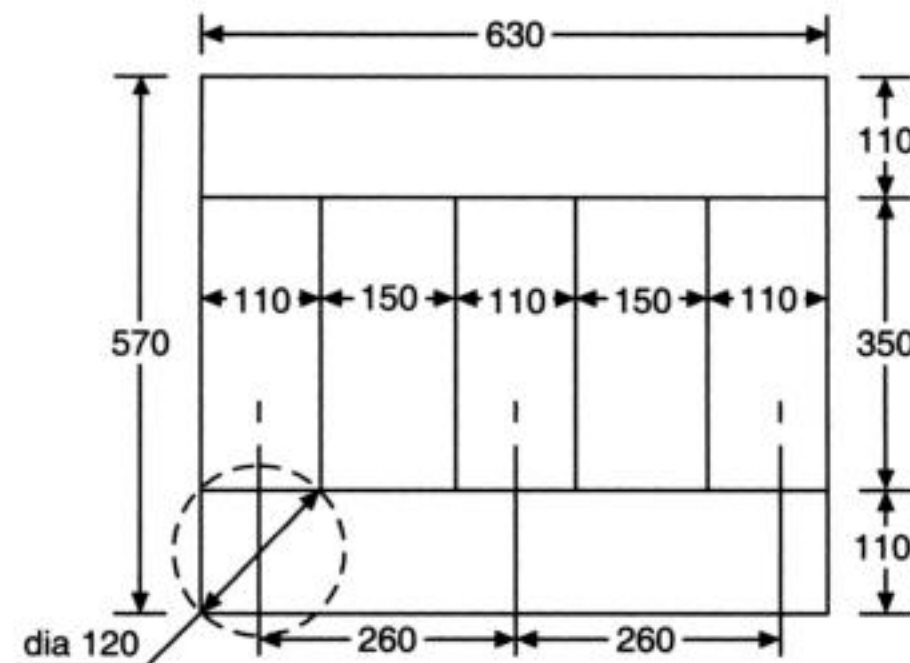


Figure 6.13 Core, yoke and frame of 63 kVA aluminium transformer (all dimensions in mm).

The dimensions of the core assembly and window chosen are as follows:

$d = 120 \text{ mm}$; horizontal distance of core limb and yoke width
 = 110 mm ; window width = 150 mm ; window height = 350 mm ;
 $D =$ distance from centre to centre of adjacent limbs = 260 mm .

Overall width of core and yoke assembly = 630 mm ; overall height of core assembly = 570 mm . Check whether the windings can be accommodated with the clearance required and find the percentage reactance of transformer to make sure that it is within the limit.

L.V. winding: Number of turns in L.V. winding

$$= \frac{\text{Voltage per phase}}{\text{Voltage per turn}}$$

$$= \frac{250.3}{3.4} = 73.6, \text{ say } 74$$

Diameter of core = 120 mm; distance between core and L.V. = 3.5 mm; inside diameter of L.V. = $120 + 2 \times 3.5 = 127$ mm.

$$\text{L.V. current} = \frac{63 \times 1000}{\sqrt{3} \times 433} = 84 \text{ A per phase being star-}$$

connected. Current density for aluminium conductors is taken as 1.5 A/mm^2 .

Area of conductor $a_2 = \frac{84}{1.5} = 56 \text{ mm}^2$. Choose a conductor of two rectangular strips each of $6.3 \times 4.5 \text{ mm}$ with paper insulation on the conductor and with layout as shown in Figure 6.14.

The conductor size will be 6.55 mm lengthwise and $4.75 \times 2 = 9.5 \text{ mm}$ widthwise for each layer of L.V. For 74 turns, choose two layers each of 37 conductors. Then height of L.V. over copper = $37 \text{ turns per layer} \times 6.55 = 242 \text{ mm}$; thickness of coil = $9.5 \times 2 = 19 \text{ mm}$.

Outside diameter of L.V. = $127 + (2 \times 19) = 165 \text{ mm}$

Mean diameter = $127 + 19 = 146 \text{ mm}$

Mean length of turn = $\pi \times 146 = 459 \text{ mm}$

H.V. winding: Number of turns in H.V. winding

$$= \frac{11000}{250.3} \times 74 = 3253, \text{ say } 3256;$$

$$\text{Line current} = \frac{63000}{\sqrt{3} \times 11000} = 3.31 \text{ A}$$

$$\text{Current per phase in H.V. winding} = \frac{63 \times 1000}{3 \times 11000} = 1.91 \text{ A}$$

Current density for aluminium conductors is taken as 1.5 A/mm^2 ; area of H.V. conductor

$$a_1 = \frac{1.91}{1.5} = 1.27 \text{ mm}^2.$$

Choose round conductor of diameter 1.25 mm area = 1.23 mm^2 .

Number of turns on H.V. = 3256; Choose four disc coils. Turns in each coil = $3256/4 = 814$.

Choose 18 layers and $\frac{814}{18} = 45$ turns per layer in each disc winding.

Height of H.V. winding in each disc = 45×1.5 (diameter of conductor including insulation) = 67.5 mm

Width of each coil = $18 \times 1.5 = 27 \text{ mm}$

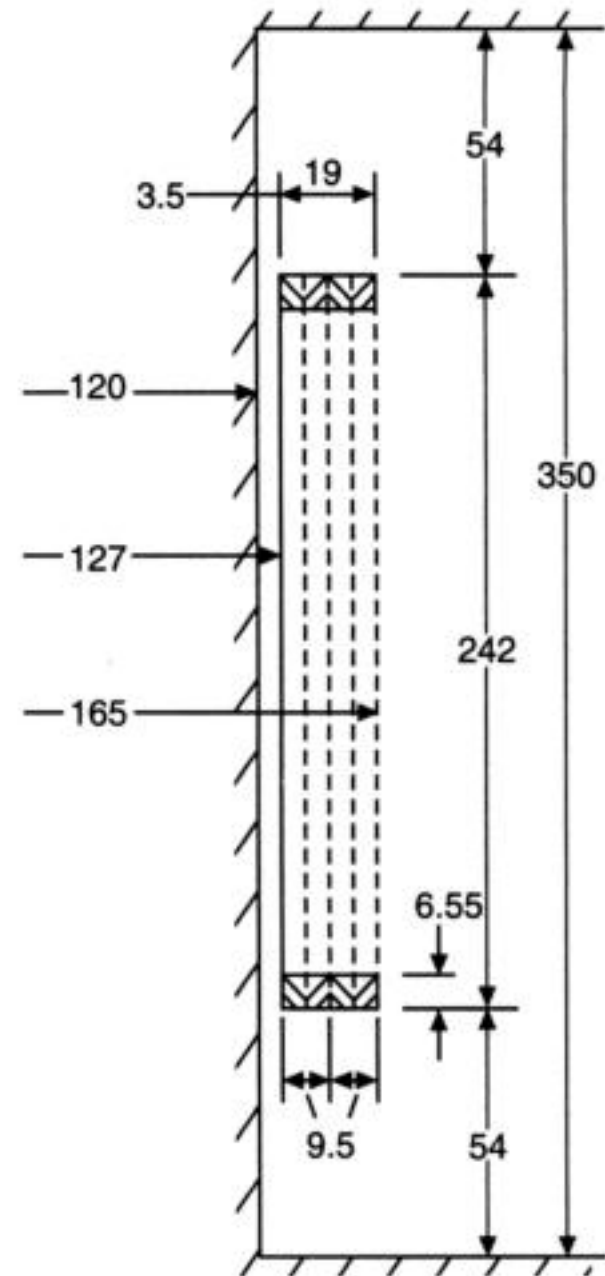


Figure 6.14 Layout of L.V. winding (all dimensions in mm).



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Testing of Transformers

7.1 TESTS ON TRANSFORMERS

The transformers designed and built in manufacturing shops are tested before they are sent to the consumers. IS:2026 (Part I):1977 specifies the tests to be carried out for this purpose. The tests are classified into: (a) type tests, (b) routine tests, and (c) special tests. Routine tests are carried out on all transformers; type tests on a few and special tests only for some special requirements.

7.1.1 Type Tests on Transformers

The following type tests are carried out on transformers.

- (a) Measurements of resistance of windings
- (b) Measurement of voltage ratio
- (c) Check voltage vector relationship
- (d) Measurement of impedance voltage, short-circuit impedance (main taping) and load loss
- (e) Measurement of no-load loss and no-load current
- (f) Measurement of insulation resistance
- (g) Dielectric tests
- (h) Temperature rise.

7.1.2 Routine Tests

Routine tests will cover all the above tests except the temperature rise or heat run test.



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Group No. 1 Phase Displacement = 0°			
Vector symbols	Line terminal markings and vector diagram of induced voltages		Winding connections
	H.V. winding	L.V. winding	
Yy_0			
Dd_0			
Dz_0			
Vector diagrams for three-phase transformers Vector rotation is counter clockwise			

Figure 7.2 Vector diagram for three-phase transformers for Group No. 1.



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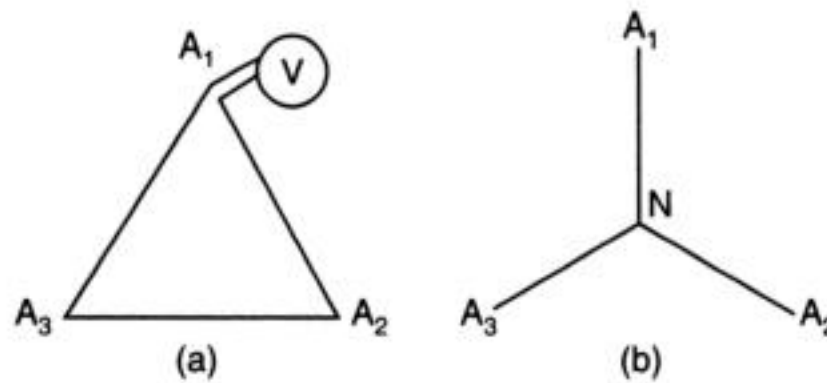


Figure 7.6 (a) Check for delta connection
(b) Check for star connection.

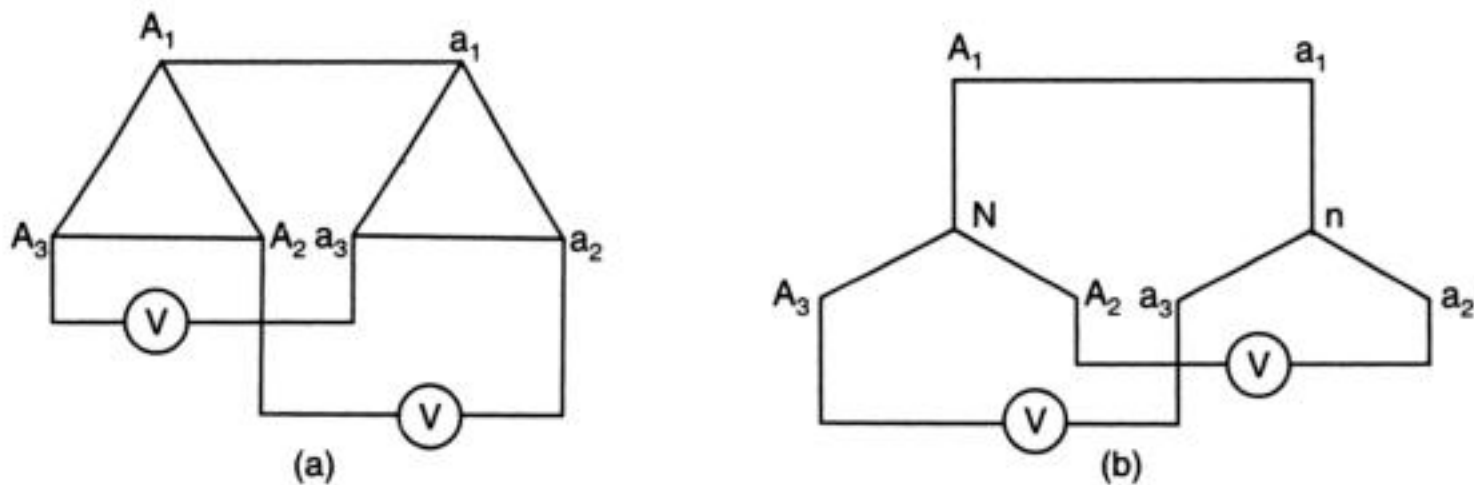


Figure 7.7 Checking phase relationships between H.V. and L.V. connections of a transformer.

7.7 MEASUREMENT OF NO-LOAD CURRENT AND NO-LOAD LOSS

The no load current and no load loss of a three-phase transformer shall be measured at the rated voltage on principal tapping and at rated frequency. Figure 7.8 shows the circuit diagram for carrying out the no load test of a transformer.

The connection diagram is shown for a single-phase transformer. Similar connections are done in the case of three-phase assuming balanced conditions. The low voltage side is supplied through a variac and the high voltage side is kept open. The voltage will be measured with a voltmeter responsive to the mean value of the voltage but the scale of the voltmeter will be marked in r.m.s. value of the sinusoidal wave having the same mean value. Another voltmeter reading r.m.s. voltage value is also connected in parallel with the average reading voltmeter. If U volts is the reading the r.m.s. reading voltmeter, and U' is the reading

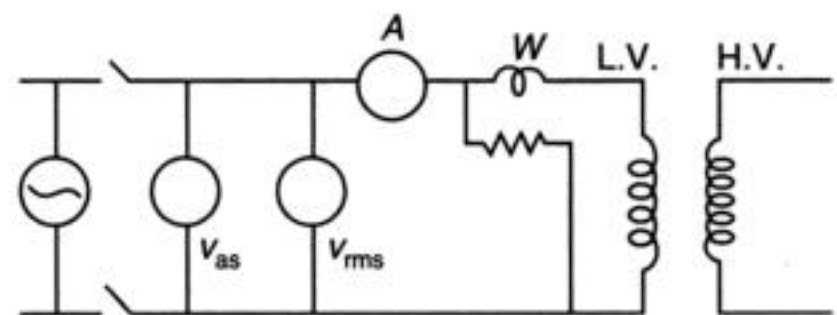


Figure 7.8 No-load test of a transformer.

of average reading voltage (line values), the loss on no load $P = \frac{P_m}{P_1 + kP_2}$

where

P_m = measured watts

P = corrected value of the wattmeter reading



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The testing apparatus for high voltage testing at power frequency consists of cascaded high voltage transformers, apparatus for controlling voltage as required, control gear and high tension connections including safety protective devices. The testing transformers are usually single-phase, core type oil immersed transformers. The principle is shown in Figure 7.10. Transformer I, L.V. coils are supplied by a variac, and the voltage applied is controlled gradually as required. The tank is earthed. One end of H.V. secondary winding of this transformer is connected to the earthed tank. From the other end of the secondary winding the connection is taken to the primary of transformer II. The terminal taken out through the high voltage bushing gives voltage approximately equal to the sum of the secondary voltages of the two transformers.

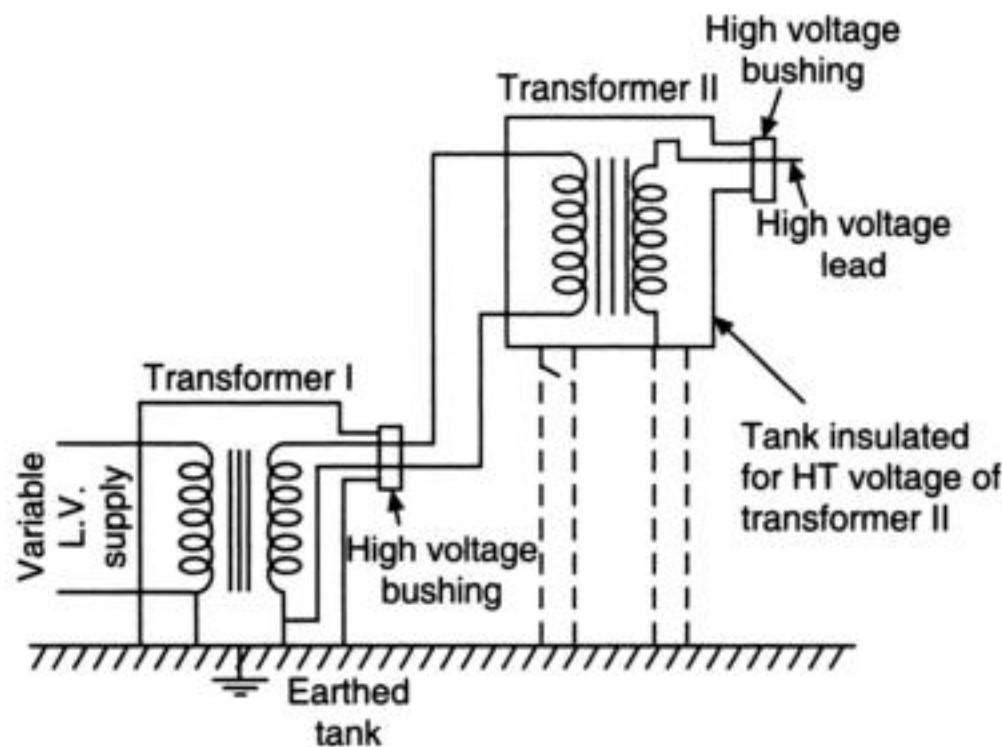


Figure 7.10 Cascade connection of transformers.

The number of transformers to be connected in cascade depends on the voltage required. Also the capacity of the transformers in cascade depends on the requirement for testing of the equipment. Generally, power frequency voltages are up to 1000 to 2000 kV. The capacity of transformers may be from 20 to 50 kVA.

(b) Induced overvoltage withstand test

The test should begin at a voltage not greater than 1/3rd the test voltage. The voltage is then increased rapidly to the full test voltage value and kept for 60 seconds. The frequency of the voltage should be twice the rated frequency of the apparatus, i.e. 100 Hz for a 50 Hz transformer. At the end of the test, the full voltage is reduced to less than 1/3rd the full voltage rapidly before switching off. The voltage is applied to the terminals of one winding of the transformer. Double or higher frequency is used in the test to avoid excess excitation current during the test. The peak value of the induced test voltage is measured. The test voltage then is peak value/ $\sqrt{2}$ volts. Induced overvoltage withstand tests from line to neutral and line to line are mentioned in IS:2126 (Part III) 1977 for various high voltages for equipment.

The double frequency (100 Hz) supply for the test can be obtained from a sinusoidal alternator rated at that frequency, or from a high frequency generator circuit.

This set-up tests the layer insulation of the transformer windings.



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For ON type cooling, on full load, the transformer conditions are generally:

Average copper temperature rise measured by resistance 55°C

Hot spot temperature rise 66°C

If ambient temperature is 32°C

The hot spot temperature may be taken as $66^{\circ}\text{C} + 32^{\circ}\text{C} = 98^{\circ}\text{C}$.

7.14 TRANSFORMERS TEST DATA RECORD

In a manufacturing concern/works, the test data of transformers tested is maintained and a test certificate for the transformers tested is issued to the customers.

The data from the tests and the certificate are of the following nature:

Rating of transformer kVA; volts, amps; frequency, phases, connections, type of cooling, taps on HV.

Tests: 1. *No load test*

tap	amps	volts	watts

2. *Load loss or short-circuit test at $^{\circ}\text{C}$ temperature*

tap	amps	volts	watts

impedance	volts	at	amps at 75°C

3. *Insulation tests*

H.V. to L.V.; H.V. to earth; L.V. to earth megohms

Separate source voltage withstand test (60 second)

HV; L.V. kV

Induced overvoltage withstand test

200%	60 second	100 Hz	kV

4. Resistance per phase at $^{\circ}\text{C}$ in ohms H.V.; L.V.;

5. Vector group, polarity

6. *Turns ratio test*

Heat run test

Temperature rise after full load run of oil in $^{\circ}\text{C}$; temperature rise after full load run of resistance in $^{\circ}\text{C}$.

Calculated values

I^2R at 75°C ; Stray load loss at 75°C ;

% reactance X ; % impedance Z at 75°C ;

Percentage efficiency at unity power factor at

125%, 100%, 75%, 50% and 25% load at 75°C ;

Percentage regulation at full load on unity power factor;

Percentage efficiency at 0.8 p.f. at 125%, 100%, 75%, 50% and 25% load at 75°C .

Regulation on full load at 0.8 power factor.



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7.17 REPAIR AND MAINTENANCE OF TRANSFORMERS

The normal life of a well worked transformer can be taken as 30 years. It may serve longer if operated with care. It may die prematurely if operated with negligence. Rigid inspection and preventive maintenance of transformers is necessary to ensure long life. The main object of maintenance of a transformer is to maintain its insulation in good condition.

Factors affecting the insulation of a transformer are: moisture, presence of oxygen, solid impurities.

It is necessary to carry out inspection of transformers for their maintenance. This consists of (i) external inspection and (ii) internal inspection.

(i) The external inspection is the inspection of parts and auxiliaries of the transformer that can be examined without opening the tank or lowering oil but with the transformer taken out of service. Megger tests, ratio tests, water flow tests, taking out sample of oil and testing it; inspection of bushings, breathers, and oil level, tank, gaskets, diaphragm, foundations, ground wire and all auxiliary apparatus can be examined. Check condition of oil circulating pumps, air blowers, off-load tap changers, on-load tap changers, protective devices, oil gauges, pressure relief device, etc.

Transformer oil: checking and testing

The deterioration of insulating oils is generally due to oxidation especially when the transformer works under high temperature conditions. Oxidation is due to the formation of acids, sludge and water which accompanies the chemical change.

Samples of transformer oil are taken carefully and inspected for colour and odour. Cloudiness in oil may be due to suspended moisture or suspended solid matter; dark brown colour may indicate dissolved asphaltiness; green colour indicates dissolved copper compounds; acrid smell indicates the presence of volatile acids.

The oil samples should be tested as follows:

- (a) The dielectric strength of oil should be tested as per IS:335-1953. The oil shall withstand a test voltage of at least 30 kV for one minute without breakdown.
- (b) Crackle test for free water should be performed as per IS:335-1953. The test is only qualitative.
- (c) The acidity of oil shall be determined as per IS:1866-1961. The limits of permissible acidity are:
 - (i) Acidity below 0.5 mg KOH/g: No action need be taken if oil is satisfactory in all other respects.
 - (ii) Acidity between 0.5 and 1.0 mg KOH/g: Oil to be kept under observation.
 - (iii) Acidity exceeds 1.0 mg KOH/g: Oil should be treated or discarded.
- (d) Sludge test: The traces of solid matter in oil samples may be examined as per IS:1866-1961.

The insulation resistance is measured by a megger along with the temperature. This is because the insulation resistance (in megohms) gets reduced to nearly half for every 10°C



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8.3 RATING OF MOTORS

The motors shall be capable of giving the rated output at rated value of terminal voltage $\pm 5\%$ and rated frequency $+1\%$. Some of the preferred output ratings for ac induction motors up to 110 kW are 1.5, 3.7, 5.5, 7.5, 11, 15, 30, 37, 75, 90 and 110 kW. The detailed sizes in between are mentioned in IS:325-1996. In case of ac machines, the minimum rated output related to the rated voltages is recommended as follows:

<i>Rated voltage</i> kV	<i>Minimum rated output</i> (kW or kVA)
3.3	150
6.6	300
11.0	750

8.3.1 Duty and Rating

The duty of a motor indicates the load on the motor including no load, rest and de-energised periods. The classification of duties of the motor in the IS:325-1996 standard is as follows:

S_1 Continuous duty: Operation of the motor at constant load to reach steady temperature.

S_2 Short time duty: Operation at constant load for a short period followed by rest to cool down to the original starting temperature.

S_3 Intermittent periodic duty: A sequence of identical duty cycles each of constant load and rest period.

S_4 Intermittent periodic duty with starting: Intermittent duty cycle consisting of a starting period, constant load period and rest period.

S_5 Intermittent periodic duty with starting and electric braking.

S_6 Continuous duty with intermittent periodic loading.

S_7 Continuous duty with starting and electric braking.

S_8 Continuous duty with periodic speed changes.

8.4 TEMPERATURE RISE

The specifications of a motor include the permissible temperature rise for its operation. The rise is considered with reference to an ambient temperature of 40°C . The permissible values of temperature rise for ac windings of induction motors of capacities less than 5000 kW output for the class of insulation used are as follows:

A 60°C ,	E 75°C ,	B 80°C	
A 60°C ,	E 70°C ,	B 80°C	for slip rings.

The temperature measurement is done by the resistance method.

The hot spot temperature will be 10°C higher than the temperature measured by the resistance method. This is corresponding to the temperature which the class of insulation can stand.



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limited to 1.8 Wb/m^2 . The depth of the stator yoke is chosen such that the flux density in the yoke is not more than 1.2 to 1.3 Wb/m^2 . Knowing D , d_s , depth of slot and d_y , depth of yoke of the stator, the outside diameter is given by

$$D_o = D + 2d_y + 2d_s \quad (8.13)$$

8.8 STATOR WINDING

For three-phase induction motors, the integral slot winding is used. Single-layer winding of mush type is common for small motors; double-layer winding, however, is mostly used. Full pitch or chorded winding is also used.

8.9 DESIGN OF ROTOR CORE

The diameter of the rotor core is D_r . The number of slots used in the rotor should be carefully chosen so as to avoid crawling, cogging, vibration or noise.

8.9.1 Choice of Slot Combination of Stator and Rotor

Harmonic field effects on the performance of induction motor are of the following kinds:

(i) *Asynchronous crawling*: Space harmonics of the winding m.m.f. create revolving fields which induce secondary current and produce torques having more poles and therefore lower synchronous speeds. As the motor accelerates through one of these harmonics, it causes a dip in the torque speed curve of the motor; there is also a tendency to have 'asynchronous crawling'. To reduce asynchronous crawling

$$S_2 \nless 1.25 S_1; \quad S_2 - S_1 \neq \frac{p}{2}$$

where S_1 = slots in the stator; S_2 = slots in the rotor; p = number of poles.

(ii) *Locking and synchronous crawling*: If two of the separate harmonics have the same number of poles, pulsating torques will be produced as they slip past each other. When their speeds coincide, there will be locking or cogging or there will be a tendency to run at subsynchronous speed and cause 'synchronous crawling'. To avoid this $S_1 \neq S_2$; also if S_2/S_1 = full number, there is a tendency for synchronous crawling, vibration and noise. Avoid S_2 exceeding S_1 by 50 to 60%. To reduce synchronous torque, $S_2 \neq 3pK \pm p$; $S_2 \neq 3pK$, where K = integer; $S_2 - S_1 \neq \pm 2p$. To avoid locking $S_2 - S_1 \neq \pm 3p$.

To reduce the effect of slot harmonics, $S_2 \neq S_1 \pm p$;

$$S_2 \neq S_1 \pm \frac{p}{2}; \quad S_2 \neq \frac{S_1}{2} \pm \frac{p}{2}$$

(iii) *Magnetic noise and vibration*: If two harmonic fields differing with number of poles = 2 coexist in the air-gap, magnetic unbalanced force will be produced and vibrations are produced in the rotor. $S_2 - S_1 \neq \pm 1$



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Performance calculations:

Performance calculations are done from the equivalent circuit under the full load, and starting conditions. If necessary, calculations may also be done under maximum torque conditions.

42. Calculate the no-load current and no-load power factor.
43. Calculate the short-circuit current.
44. Calculate the full-load current.
45. Calculate the stator copper loss at full load.
46. Calculate the rotor copper loss at full load.
47. Calculate the slip on full load.
48. Calculate the power factor.
49. Calculate the efficiency on 25%, 50%, 75% and 100% full load.
50. Calculate the full-load torque.
51. Calculate the starting torque.
52. Find the starting torque/full-load torque.
53. Calculate the maximum torque or pull-out torque/full-load torque.
54. Calculate the temperature rise.

The following formulas may be recalled for calculations:

$$(i) \quad \frac{\text{Rotor copper loss}}{\text{Rotor input}} = \text{Slip}$$

$$(ii) \quad \text{Torque} = \text{Rotor input} = \frac{\text{Rotor copper loss}}{\text{Slip}} \text{ synchronous watts}$$

$$(iii) \quad \text{Torque} = \frac{s \alpha}{s^2 + \alpha^2};$$

$$(iv) \quad \text{Torque is maximum when } s = \alpha = \frac{r_2'}{x_2'}$$

$$(v) \quad \frac{\text{Starting torque}}{\text{Full-load torque}} = \left(\frac{\text{Starting current}}{\text{Full-load current}} \right)^2 \times \text{Full-load slip}$$

At start, slip = 1.0

8.13.1 Design of Slip Ring Type Induction Motors

In the case of slip ring type motors, the rotor is star connected. A double layer winding with a suitable number of slots accommodating an integral number of conductors per slot is chosen. The voltage between slip rings (line) is limited to 500 volts. The ratio of turns can be found out

and the rotor parameters calculated referred to the stator. They are to be multiplied by $\left(\frac{T_1}{T_2} \right)^2$.

Copper conductors of suitable size are used for the windings. The rest of the procedure is the same as in the case of squirrel cage induction motors.



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Choosing $D = 165$ mm; $L = \frac{3.62 \times 10^6}{165^2} = 133$ mm or take $L = 140$ mm

Thus frame 160 M is chosen with main dimensions as—

$$D = 165 \text{ mm; } L = 140 \text{ mm; outside diameter } D_o = 260 \text{ mm}$$

No ducts in the core.

$$\text{Pole pitch } Y = \frac{\pi D}{p} = \frac{\pi \times 165}{4} = 129.6 \text{ mm}$$

$$\text{Flux per pole } \phi_m = \bar{B}YL = 0.45 \times \frac{129.6}{1000} \times \frac{140}{1000} \times 1000 \text{ mWb} = 8.16 \text{ mWb}$$

$$\begin{aligned} \text{Number of turns per phase} &= \frac{415}{4.44 \times 0.955 \times \phi_m \times 50} = \frac{415}{4.44 \times 0.955 \times 8.16 \times 10^{-3} \times 50} \\ &= 239.8 \end{aligned}$$

Take turns per phase $T_1 = 240$

Number of slots per pole per phase = 3; total slots in the stator = 36

$$\text{Slot pitch} = \frac{\pi \times 165}{36} = 14.4 \text{ mm}$$

Slot pitch is 14.4 mm so that the slot the width can be about half of it, leaving the tooth width sufficient enough from mechanical considerations as well as to avoid much saturation. Keeping the maximum flux density within the permissible limits of the material used,

$$\text{Conductors per slot} = \frac{240 \times 2 \times 3}{36} = 40$$

$$\text{Full-load current } I \text{ per phase} = \frac{9.8 \times 1000}{3 \times 415} = 7.87 \text{ A}$$

Taking current density as 4 A/mm²,

$$\text{Area of conductor} = \frac{7.87}{4} = 1.97 \text{ mm}^2; \quad \frac{\pi d^2}{4} = 1.97; \quad d^2 = 2.5 \quad \text{or} \quad d = 1.58 \text{ mm}$$

Choose a conductor of diameter 1.6 mm with medium enamelled covering. With covering, the overall diameter $d = 1.711$ mm

$$\text{Area of conductor to be accommodated} = \frac{\pi}{4} \times 1.711^2 = 2.3 \text{ mm}^2$$

$$\text{Number of conductors per slot} = \frac{240 \times 2}{12} = 40$$

$$\text{Area required for conductors in the slot} = 40 \times 2.3 = 92 \text{ mm}^2$$



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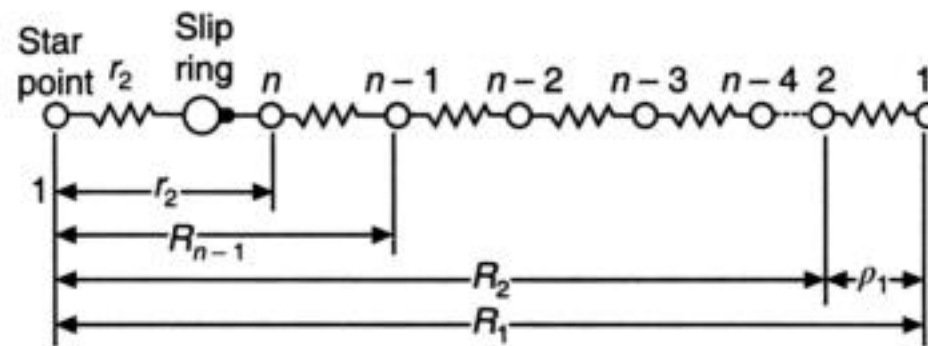


Figure 8.9 Rotor resistance starter steps.

At start $s_1 = 1$

$$R_1 = \frac{r_2}{s_{\max}}; \gamma = \sqrt[n-1]{s_{\max}}$$

and

$$\rho_1 = R_1(1 - \gamma)$$

$$\rho_2 = \gamma \rho_1$$

$$\rho_3 = \gamma \rho_2, \text{ etc.}$$

(8.22)

EXAMPLE 8.5 Design a rotor resistance starter for the motor in Example 8.3. Rotor resistance per phase $r_2 = 0.0315 \, \Omega$; full-load rotor current = 153.5 A; slip at full-load $s_{\max} = 0.0285$. Use 7 studs, i.e. 6 sections or 6 steps.

Solution:

$$R_1 = \frac{r_2}{s_{\max}} = \frac{0.0315}{0.0285} = 1.105 \, \Omega$$

$$\gamma = \sqrt[6]{0.0285} = 0.55$$

Substituting in the above expression, the resistance of the sections of the starter steps can be found out.

$$\rho_1 = 1.105(1 - 0.55) = 0.498$$

$$\rho_2 = 0.55 \times 0.498 = 0.275$$

$$\rho_3 = 0.55 \times 0.275 = 0.151$$

$$\rho_4 = 0.55 \times 0.151 = 0.083$$

$$\rho_5 = 0.55 \times 0.083 = 0.044$$

$$\rho_6 = 0.55 \times 0.044 = 0.024$$

$$r_2 = \frac{0.031}{1.106} \, \Omega$$

This tallies with $R_1 = 1.105 \, \Omega$.

8.21 TO ADAPT WINDINGS TO A GIVEN FRAME

Often it is necessary in a design office to choose windings for the same frame to provide a different output, frequency and voltage. If T_1 is the number of turns per coil for a standard motor



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At 15% lower voltage and 75% load, performance is all right; at still 10% lower voltage, the performance is all right but the temperature starts rising at higher voltages and performance is poorer; above 15% overvoltages, the motor gets heated and failure may occur.

- (iii) Derated motor with appropriate pump rating:
Performance at 15% lower voltage is better; at still lower voltages, the performance will be poorer; temperature limit depends on the design.
At higher voltages, the performance will be poorer.
- (iv) Derated motor with small pump:
This is the worst case from the performance point of view but best with reference to temperature rise limitations.

It is thus seen that if the motor is derated and designed accordingly using large quantities of iron and copper, it can avoid failures and limit the temperature rise, but the performance decreases. The cost of the motor also increases. The designer should consider the extra material cost as well as energy used due to poor performance and limit the permissible balance.

If proper voltage control is effective on supply voltage, agricultural motors should have a higher performance level at rated voltage. Pump rating should be proper and not smaller. The motors should be designed for higher thermal reserve.

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- (iii) Rope and pulley
- (iv) Calibrated machine

9.6 LOAD TESTS

The motor is loaded to 125%, 100%, 75%, 50%, and 25% of the full-load value and readings are taken of current, voltage, watts input (wattmeters), and speed.

The power factor, speed from slip measurement, efficiency and temperature rise are calculated.

Slip is measured by (a) stroboscope method or (b) slip coil method or (c) by magnetic needle method.

Power factor is measured by:

- (i) Watts to volt-ampere ratio
- (ii) Two-wattmeter method
- (iii) Power factor method

$$(i) \text{ Power factor} = \frac{\text{watts}}{\sqrt{3 \times \text{volts} \times \text{amperes}}} \quad (9.2)$$

$$(ii) \text{ Power factor} = \frac{1}{\sqrt{\left(1 + 3 \left[\frac{W_1 - W_2}{W_1 + W_2} \right]^2\right)}} \quad (9.3)$$

where W_1 = higher of the two wattmeter readings
 W_2 = lower of the two wattmeter readings

Methods of loading the motor:

- (a) Brake method
- (b) *Dynamometer method:* The output of the induction motor is given by

$$\text{kW} = \frac{T \times \text{rpm}}{974} \quad (9.4)$$

where T is the torque in kg-m.

- (c) *Calibrated machine:* The induction motor under test may be coupled to the calibrated generator: the efficiency curve of this generator is known.
- (d) If a calibrated generator is not available, an uncalibrated machine is used and then its efficiency is also determined first and used to calculate the loading performance of the motor.
- (e) *Duplicate machines:* This test uses two machines. It is also known as pump back test because the power taken from the line is returned again to the same system except for the losses in the test motor and generator and the losses in the power supply units.



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$$\cos \phi_0 = \frac{250}{\sqrt{3} \times 415 \times 3.5} = 0.1; \phi_0 = 84.3^\circ$$

- (b) Stator resistance per phase = $R_1 = 1.5 \Omega$;

Stator copper loss on no load = $3.5^2 \times 1.5 = 18.375$ W per phase. Core, friction and windage loss = no load loss – stator copper loss
 $= 250 - 3(18.375) = 194.875$ W.

If friction and windage loss is given or from the readings of watts vs. (voltage)² are plotted and the intercept for zero voltage is known, friction and windage loss can be determined separately.

Then core loss can be separated.

- (c) Resistance r_m in the parallel branch of the equivalent circuit

$$r_m = \frac{\text{voltage per phase}}{I_0 \cos \phi_0} = \frac{415/\sqrt{3}}{3.5 \times 0.1} = 684.5 \Omega$$

and reactance in the magnetizing branch

$$x_m = \frac{\text{voltage per phase}}{I_0 \sin \phi_0} = \frac{415/\sqrt{3}}{3.5 \times 0.995} = 68.30 \Omega$$

- (d) Input under locked rotor condition = 1660 W at 115 V and the current is 13 A

$$\text{Input} = \sqrt{3} \times 115 \times 13 \times \cos \phi_s$$

Hence
$$\cos \phi_s = \frac{1660}{\sqrt{3} \times 115 \times 13} = 0.64$$

- (e) Short-circuit current with full voltage applied = $13 \times \frac{415}{115} = 46.9$ A

$$V_{ph} = 415/\sqrt{3} = 239.6 \text{ V}$$

$$\text{Equivalent impedance } Z_e = \frac{\text{voltage per phase}}{\text{short-circuit current}} = \frac{239.6}{46.9} = 5.11 \Omega$$

- (f) Equivalent resistance $R_e = Z_e \cos \phi_s = 5.11 \times 0.64 = 3.27 \Omega$

$$R_1 = 1.5 \Omega; R'_2 = 3.27 - 1.5 = 1.77 \Omega$$

- (g) The leakage reactance $X_1 = \sqrt{(Z_e^2 - R_e^2)} = \sqrt{(5.11^2 - 3.27^2)} = 3.92 \Omega$

This can be approximately divided half and half between the stator and the rotor. Thus $x_1 = 3.92/2 = 1.96 \Omega$; and $x'_2 = 1.96 \Omega$.

EXAMPLE 9.2 For the motor in Example 9.1, the following readings were obtained when loaded:



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III. Induction Motor Performance Calculations

Frame	Rating		
	No-load losses	=	watts
	$I_0^2 R_1$	=	watts
	Constant losses	=	(diff. of two above) watts.

Stator copper loss $I_1^2 R_1$ (at 75°C) = Stator losses = constant losses + stator copper loss

Input to motor watts

Rotor input = stator input – stator losses = watts

$I_2'^2 R_2$:	Rotor copper loss = Rotor input $\times \frac{\text{slip rpm}}{\text{synchronous speed}}$
	Stray load loss = 0.5% of motor input = watts
	Total losses in motor watts
	Input to motor watts
	Output (difference between Input and total losses) watts

kW output | Full load amps | % Efficiency | Power factor | % slip

Stator winding temperature

rise by resistance $(t_2 - t_a)$ $\frac{R_2 - R_1}{R_1} (235 + t_1) + t_1 - t_a$

Rotor winding temperature

rise by resistance $(t_2 - t_a)$ Similar expression—
for rotor resistance—

Notation as in Example 9.16

Temperature by thermometer	Body	Stator core	Stator winding	Rotor winding	Slip rings	Bearings
Final temperature $^\circ\text{C}$						
Temperature rise $^\circ\text{C}$						

Momentary overload test after heat run;

60% excess torque for 10 seconds

Momentary overspeed test

Starting current = — —times Full load current amps
at volts

Starting torque at volts.

Full-load torque = $\frac{974 \times \text{kW}}{\text{FL rpm}}$ kg-m.

Starting torque = $\left\{ \frac{\text{Rated volts}}{\text{Test volts}} \right\}^2 \times \frac{\text{Length of (m)} \times \text{kg}}{\text{Full-load torque}}$
= (times) full-load torque



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Solution:

$$\text{Full-load armature current} = \frac{500 \times 1000}{\sqrt{3} \times 3300} = 87.6 \text{ A}$$

$$\text{Resistance of armature per phase} = 0.2 \text{ } \Omega$$

$$\text{Armature copper loss} = 3 \times 87.6^2 \times 0.2 = 4600 \text{ W}$$

$$\text{Short-circuit loss} = 13,600 \text{ W}$$

$$\text{Friction and windage loss} = 5000 \text{ W}$$

$$\text{Stray load losses} = 13,600 - 4600 - 5000 = 4000 \text{ W}$$

The various losses in the machine can be added:

$$\text{Armature copper loss} = 4600 \text{ W}$$

$$\text{Friction and windage loss} = 5000 \text{ W}$$

$$\text{Stray load loss} = 4000 \text{ W}$$

$$\text{Core loss} = 12,000 \text{ W}$$

$$\text{Field copper loss} = 9680 \text{ W}$$

$$I_f^2 R_f = 22^2 \times 20$$

$$\text{Exciter loss} = 1000 \text{ W}$$

$$\text{Total loss} = 36,280 \text{ W}$$

$$\text{Output of the generators on full-load at 0.8 power factor} = 500 \times 1000 \times 0.8 = 400,000 \text{ W}$$

$$\text{Input} = \text{Output} + \text{Losses} = 400,000 + 36,280 \text{ W} = 436,280 \text{ W}$$

$$\text{Efficiency of generator} = \frac{400,000}{436,280} \times 100\% = 91.7\%$$

12.17 HEAT RUN TESTS ON SYNCHRONOUS MACHINES

- (a) The synchronous machine is driven at its rated speed and tested, under the following conditions to find the temperature rise of the machine parts.
- Machine operating unexcited.
 - Machine operating as a generator on short-circuit with armature current equal to the rated full load current.
 - Machine operating as a generator on open-circuit with its armature voltage equal to the rated voltage or equal to the voltage behind the Potier reactance at rated load.

In the case of armature parts, find the temperature rise at steady state final conditions under open-circuit and short-circuit conditions, add them and from this sum subtract the final steady state temperature rise under unexcited conditions; this gives the final steady state temperature rise of armature parts at the rated load.

For the field winding, plot the final temperature rises obtained under the above three conditions (i), (ii), and (iii) of the tests. The final temperature rise of the field windings is obtained by extrapolation from the above curve, considering the point at rated excitation.



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14.11 ARMATURE FAULTS IN DC MACHINES

The possible faults that can develop in the armature winding are:

- (a) Short-circuit of a coil or coils in the armature
- (b) Open-circuit in one of the armature coils
- (c) An 'earth' on one or more armature coils.

(a) *Short-circuited coil:* The short-circuit may take place between the risers, or between adjacent turns of a multiturn coil. The effect is intense local heating of the faulty coil. Many times, the fault may burn out the coil and cause open-circuit of the coil.

(b) *Open-circuited coil:* The effect will be marked when on load. Half the winding between the brushes having an open-circuited coil carries no current while the other half, having sound coils, carries double the normal current. When the faulty (open-circuited) coil passes below the brush, the current in the sound coils changes from double to zero and vice versa. This increases the reactance voltage and causes vicious sparking at the brushes when the open-circuited coil passes under the brushes. On stopping the machine, it will be observed that there is pitting in the commutator segments connected to faulty coil and those one pole pitch apart.

(c) *Earthed coil:* If there is only a single earth, the effect is not serious and noticeable. However, if two separate coils on the armature are earthed, there is unbalanced current in that part of the winding, local heating is caused, the winding gets short-circuited and sparking occurs at the commutator.

14.11.1 Method of Testing Armature Faults

(a) The short-circuit and (b) open-circuit in armature coils can be tested for faults and the faulty coils located by means of a 'drop test' on the armature with the armature stationary. This test may be done with the armature in position or removed from the bearings. Current is fed to the armature from a low voltage source. The diagram of connections is shown in Figure 14.9.

A voltmeter is connected by prongs to adjacent commutator segments and the voltage between the consecutive commutator segments is measured. If the coil connected between the commutator segments is shorted, there will be no voltage drop across this or if there is a partial fault, the voltage drop will be very low compared to the voltmeter readings between other commutator segment pairs.

In the case of an *open-circuit* of the coil, there is no voltmeter reading between commutator segment pairs (successive) if the reading are taken in the commutator half having the open-circuit coil. The voltmeter will read only when the voltmeter contacts are passed from commutator segment to segment and they are across the commutator contacts where the coil is open-circuited. Here the voltmeter will read full supply voltage because one commutator segment is connected to positive, while the other one gets supply from the negative side, there being disconnection between the two commutator segments. In lap

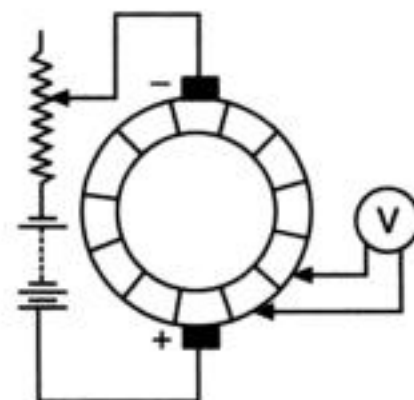


Figure 14.9 'Drop test' on armature coils.



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15.2 MANUAL VERSUS COMPUTER AIDED DESIGN

In order to understand the computer-aided approach to design of rotating electrical machines, one must make a clear distinction between the manual design and the computer-aided design of the machine. In the manual design process, the calculation work is rather slow and can be inaccurate at times due to human limitations. But the capability of the versatile brain of the designer is continuously utilised to give shape to the design and to arrive at the desired solution quickly with a few number of iterations. This means that the power of the human brain and the accumulated knowledge and experience of the designer is used to review a large number of inter-related phenomena to check that all design requirements are met and, at the same time, a reasonable and satisfactory design is obtained considering the performance requirements and the cost. This is particularly important for such electrical machines where the electromagnetic, mechanical, thermal and dielectric phenomena are to be closely co-ordinated to arrive at the proper design. The designer, with his vast experience, knowledge and exceptional skills, can achieve this task.

In contrast to this, the computer-aided design, or the design by computer, is based on an entirely different approach. The modern computer can perform a very large number of calculations to the required degree of accuracy in an unimaginably short time. It can accept any amount of sophistication and iteration requirements in performing the various calculations as well as carry out logical decisions to arrive at the optimum design. However, the computer does not have the human intelligence and even the most elaborate computer programs cannot be made to include human experience to manipulate the design with all its complexities and inter-related phenomena, mentioned above, to achieve the desired objective. A computer is required to be suitably “programmed” to carry out the design and it will strictly adhere to the program, furnishing the results at the end of the program. Hence, the computer’s capability is essentially decided by the “program” that is used for the design and nothing else. This distinction between the human and computer approaches to designs must be appreciated by the student when he embarks upon preparing the computer program for the design of a machine.

With the gradual evolution of powerful computers in the last thirty years and their availability at an affordable cost, it has become possible to incorporate several human capabilities in the computer programs for the design of machines. It must, however, be noted that the computer is an aid to the designer and not by itself a designer.

15.3 APPROACH TO COMPUTER AIDED DESIGN

We begin with the assumption that the student is familiar with the conventional design procedures for rotating electrical machines such as the squirrel cage induction motors and alternators (refer earlier chapters). In order to develop a computer program for the design of a machine, a step-by-step approach is required to be followed. The first step is to evolve a “calculation program” for the design commonly known as the “analysis program”. In order to prepare the analysis program for a design, the following inputs are generally needed:

1. Performance requirements of the machine, such as efficiency, torque, slip, reactances, etc.
2. Various dimensions of the machine required to calculate its performance. These can be diameters, lengths, slot shapes, winding details, and are tentative.



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to give reasonably accurate prediction of temperature rise in different parts of the machine. This is due to difficulties in correctly predicting the behaviour of the cooling medium, like air, in different parts of the machine and heat exchanger as well as the heat conduction and transfer co-efficients at different regions of the machine.

In electrical machines, apart from the performance in the steady state condition like no-load, part-load, full-load, etc., behaviour under various transient conditions is also equally important. For example, the voltage dip and its recovery following the sudden load application in an alternator with a given excitation system is of considerable interest to the designer. Similarly, the currents and torques developed in an induction machine in the event of its being reswitched to a new supply system after it is disconnected from its normal bus are required to be estimated for carrying out appropriate design of the various parts of the machine. The effect of high voltage surge on the insulation strength of the stator winding of a high voltage machine needs a complex computation which can be excellently developed on the computer.

The above examples are not exhaustive but are typical to illustrate the numerous requirements to which the computer programs can be developed to help the designer in assessing the behaviour of the machine under transient conditions. Figure 15.2 illustrates a flow diagram of a step-by-step calculation of transient current developed in an electrical machine.

It is possible to combine the various programs for a machine into one complex program or work out all the programs separately and combine them manually. Depending upon the type and range of machines to be covered and the sophistication desired and economically justified, an appropriate choice has to be made concerning the way in which the computer programs are to be organised.

15.7 COMPUTER-AIDED DESIGN IN INDUSTRY

An attempt has been made in this section to illustrate the computer-aided designs that were carried out for rotating electric machines in industry based on the then author's experience. The author's firm was one of the earliest industries manufacturing electrical machines in India to employ digital computers for working out the designs. As early as mid-1960s, computer analysis programs had been developed for designs of induction machines and synchronous machines being developed by the firm. Computer facilities were not widely available in the country at that time and the computer programs prepared on punched cards were run at the computer facility of the Tata Institute of Fundamental Research, Bombay, on their mainframe computer type CDC 3600. These programs were continuously improved by adding more sophistication to get more accurate results. Subsequently, these programs were adapted to run on the computer facilities at the Physical Research Laboratory, Ahmedabad, and later at the local computer facilities. It had been then possible to run most of these programs on the facilities available in the factory premises on PDP-11 computer. With the rapid introduction of personal computers thereafter, many of the simple programs have been converted for use on these computers. Personal computers are extremely convenient for working out a large number of programs, getting quick results as well as for direct human interaction to work out several alternatives and arrive at the optimum design (interactive design). Here, the engineer directly observes the performance of the machine on the visual display unit of the computer and alters the parameters suitably to arrive at the required design.



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D2.2 Short-Circuit Ratio

The short-circuit ratio is defined as the ratio of field current to produce rated voltage on open-circuit to the field current required for rated armature current on short-circuit. This is reciprocal of per unit value of the saturated synchronous reactance.

D3 TWO REACTION THEORY OF SYNCHRONOUS MACHINES

The total mmf in synchronous machine may be split into two components—one along the pole axis or direct axis and the other at right angles to this or quadrature axis. In the case of cylindrical rotor machines, the air-gap is uniform and the reactance of the magnetic circuit along both axes is the same. The effect of armature reaction, fluxes and voltages induced can be treated in a simple way with the concept of a synchronous reactance and taking it as constant for all positions of field poles with respect to the armature. In the case of salient pole construction, however, the reluctance of the magnetic circuits on which the emfs act are different along the direct axis and the quadrature axis. The reluctance of the direct axis magnetic circuit is due to yoke and teeth of the stator, air-gap, and pole and core of the rotor. In quadrature axis, the reluctance is mainly due to large air-gap in the interpolar space.

Given armature currents produce the same fundamental m.m.f. wave regardless of the angular position of the rotor. But the fundamental flux varies with the rotor position. If the rotor is so rotated that the pole axis or the direct axis stays in line with the crest of the rotating mmf wave, low reactance or high permeance is offered and the fundamental flux wave has the greatest magnitude for a given armature current. The flux paths under the position of direct axis and the quadrature axis are shown in Figures D4(a) and (b).

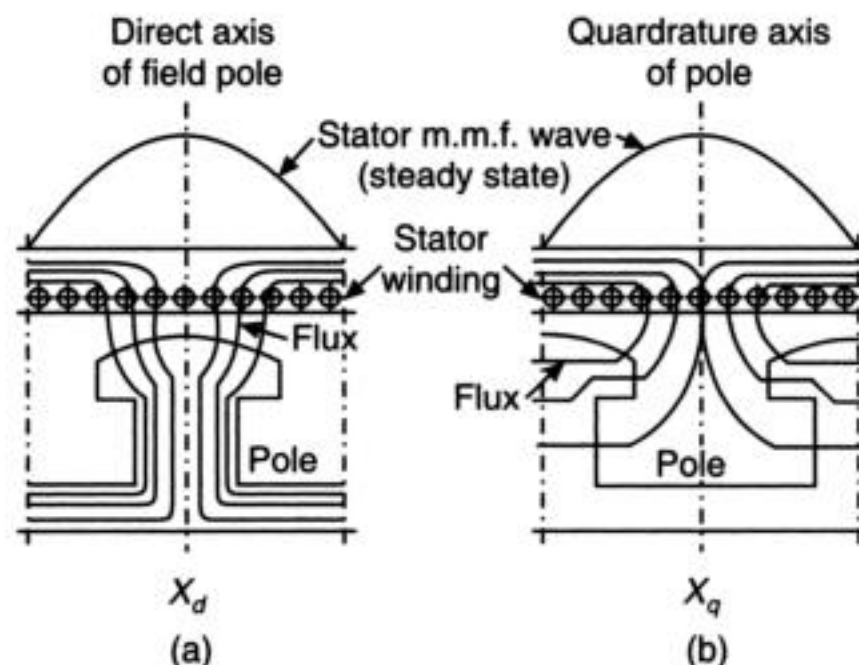


Figure D4 Stator mmf wave and flux distribution under the position of air-gap under the position of direct axis and quadrature axis of pole.

It will be seen that the magnitude of the space fundamental flux is greatest in the direct axis and the smallest in the quadrature axis. The flux linkage of the armature phase per ampere of armature current under condition of Figure D4(a) is direct axis synchronous inductance and under condition Figure D4(b) quadrature axis synchronous inductance. Multiplying by angular velocity ω , we get direct axis synchronous reactance and quadrature axis synchronous reactance. In salient pole synchronous machines $x_q = 0.6$ to $0.7x_d$. In cylindrical rotor machines, $x_q = x_d$.



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