CHAPTER 1

Basic Considerations

1.1 Design of Electrical apparatus consists mainly of furnishing data for the manufacture of the apparatus to suit a given specification using available materials economically. A designer should strive to obtain,

(i) lower cost, (ii) smaller size, (iii) wider temperature limits of operatibility and (iv) lower weight,

by judicious use of materials at his disposal.

In the design, a designer is required to have certain basic data of primary importance on which he will have to develop his design. Based on the given specification he chooses basic materials–magnetic, conducting and insulating, depending on their characteristics, availability and cost.

The design procedure starts with the assumption of certain basic quantities such as flux-density and ampere-conductors per metre or current-density (Figure 1.1). From the designed data the parameters of the apparatus are determined so that its performance and temperature-rise are calculated which are then compared with the given specification. If no satisfactory result is obtained the basic assumed quantities are suitably modified till the result is upto satisfaction. The design process is thus iterative whether done by hand or by computer.

1.2 COMPUTERS IN DESIGN

There are several benefits to be gained through the use of computer in the design of machines. A knowledge of such benefits is essential so as to assess the cost-effectiveness of such use.

(a) Once a program has been developed and fully implemented on a computer all future designs are nothing but routine computations largely independent of designer's skill. Highly trained designers are thus relieved of routine tasks and may be utilised for developmental work.

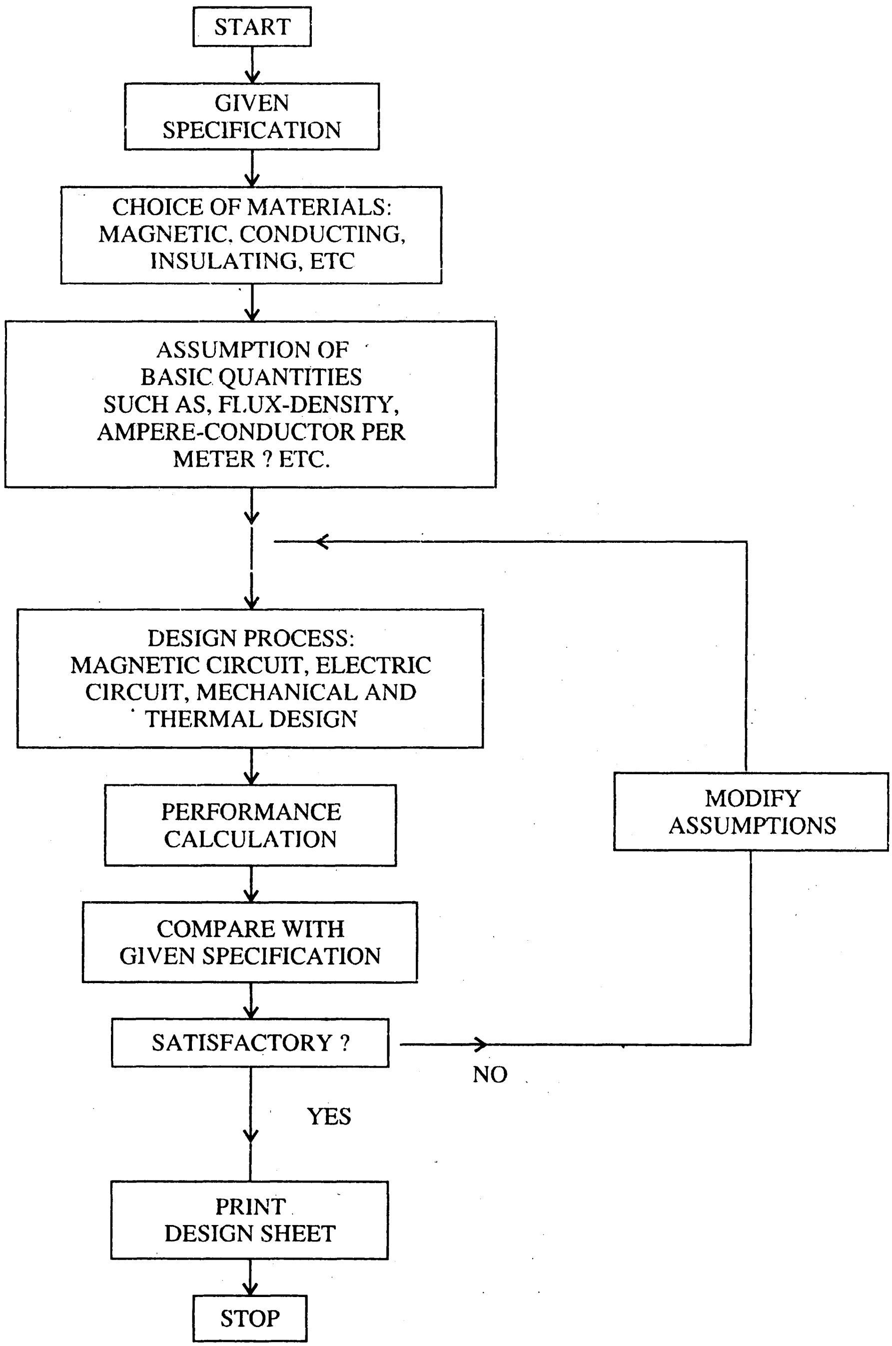


Figure 1.1 Design flow-chart.

(b) A computer can only work on exact information. Though it can reduce empiricism and handle non-linearities, it has neither the 'feel' nor the intuition of a designer. Feeding exact information to the computer means formulation of mathematical relationships between various functional variables, keeping in mind their relative importance in the design. Thus, for successful use of computer in design it is essential that the design principles are thoroughly understood. Again, computer can be effectively used as a means of this understanding, so that the mathematical relationships between the variables could be more correct.

(c) In many applications, 'total computerisation' of design is not very effective because of the difficulty in formulating accurate functional relationship's between the constructional variables. Instead, 'partial computerisation' gives better result, in which a designer breaks down the complete design process into several parts, assigns routine tasks to the computer to obtain a series of intermediate results. He uses his skill and judgement for the decisions which are dependent upon experience and human ability to detect trends, based on which he feeds further information to the computer to arrive at a final solution. Such interactive method generally gives a better design since it combines skill and judgement of the designer with the fast computing power of the computer.

(d) Computer's ability to furnish optimum design by sorting through a large number of different combinations is a welcoming feature. However, optimisation through total computerisation is often difficult specially with electrical machines due to a large number of available frame sizes, magnetic materials and wire gauges. Such approach involves so much logic that formulation is difficult and often requires storing of relatively large amount of data. Moreover, it is very difficult to get a number of designers to agree with one formulation of logic as the best one.

On the contrary, optimisation through continuous interaction between the designer and the computer has been more effective specially for electrical machines, though it is costlier in terms of operation time.

The process of design of electrical machine can be broadly divided into a few major problems :-

(i) Design of magnetic circuit,
(ii) Design of electric circuit,
(iii) Mechanical design,
(iv) Thermal design,

followed by performance analysis.

For computer-aided design, the above problems are often treated separately, even broken down into simple elements and considered as individual problem. The results are then combined.

A simple generalised design procedure is outlined in the flow-chart of Figure 1.1

(a) *Given specification consists* of performance requirements as defined by customer's need and Indian Standard Specifications.

(b) Based on given specification, the designer chooses materials–magnetic, conducting and insulating, for electrical design and other materials for frame, bearing, etc. For this, the designer must be conversant with the characteristics, availability and cost of materials needed as so to feed the computer with relevant informations.

(c) *Assumption of basic design parameters* such as, flux-density (Specific magnetic loading), ampere-conductor per meter (Specific electric loading), space-factor, stacking factor, etc. is then made and fed to the computer.
(d) *Design process* consists of analysis calculations to determine the various dimensions of magnetic and electric circuits, thermal and mechanical designs.
(e) *Predetermination of performance* of the machine is then made based on the calculated dimensions. This means calculation of machine parameters from mechanical dimensions obtained through the design process followed by calculation of performance under no-load and load conditions, determination of temperature-rise, cost etc.
(f) The next procedure is the *comparison between the calculated performance and customer's requirement.* If not satisfactory (which is generally the case at the first instance), the designer has to modify the basic assumptions so as to bring the final design closer to the objective. Such modification is not generally a simple task for there are many input parameters that can be changed, and needs skill and intuition of a designer.

1.3 STANDARDISATION AND STANDARDS

Standardisation and Standard Specifications play an important part in the choice, *design*, manufacture, and operation of any apparatus. Standardisation of apparatus presents definite advantages over that made to order.

To the manufacturer, it means reduction in cost as economy results when a number of objects are built at the same time. A planning, a production line can thus be established.

To the user, standardisation means interchangibility of equipment and spares.

To the designer, it means rigidity. The customer can not be given the whole benefit of technical possibilities and up-to-date experience till the Standards are modified.

Published Standard Specifications

In an effort to standardisation, all countries have established national rules which are revised as and when required. Such work is conducted by organisations which include representatives of manufacturers and users : in India by the Indian Standards Institution; in Great Bretain by the British Standards Institution ; in the U.S.A. by the American Standards Association. Again International Electrotechnical Commission (IEC) created jointly by various countries publishes internationally-accepted recommendations so that a product can be sold in other countries.

A few important Indian and IEC Standards related to design of transformers and electrical machines are given below :–

Indian Standards These are issued by Indian Standards Institution, Manak Bhavan 9, Bahadur Shah Zafar Road New Delhi 110001.

1. IS 1271-1958 : Classification of insulating materials for electrical machinery and apparatus in relation to their thermal stability in service.
2. IS 1885 (Part XXVIII) - 1973 : Electrotechnical vocabulary—Transformers.
3. IS 2026-1962 : Power Transformers.
4. IS 1180-1972 : Three-phase distribution transformers upto and including 100-kVA 11-kV outdoor type.

5. IS 3639-1966 : Fittings and accessories for Power transformer.
6. IS 4722-1968 : Rotating electrical machines.
7. IS 1885 (Part XXXV)-1973 : Electrotechnical vocabulary–Rotating machines.
8. IS 325-1970 : Three-phase induction motors.
9. IS 4691-1968 : Degrees of protection provided by enclosures for rotating electrical machinery.
10. IS 6362-1971 : Designation of methods of cooling for rotating electrical machines.
11. IS 5422-1969 : Turbine-type generators.
12. IS 1231-1974 :Dimensions of three–ph. foot-mounted induction motors
13. IS 3003 (Part I)-1966 and 3003 (Part II)-1969 : Carbon brushes for electrical machine.
14. IS 5571-1970 : Guide for selection of electrical equipment for hazardous areas.
15. IS 3682-1966 : Flame-proof alternating current motors for use in mines.
16. IS 4800-1968 : Specification for enamelled round wires.
17. IS 6160-1971 : Specification for rectangular conductors for electrical machines.

IEC Standards : These are issued by the International Electrotechnical Commission, 1 Rue de Varembe′, Geneva, Switzerland.

1. IEC 27-1971 : Letter symbols to be used in electrical technology, Part I – General.
2. IEC 38-1975 : IEC standard voltages.
3. IEC 50-1973 onwards : International electrotechnical vocabulary.
4. IEC 85-1957 : Recommendations for the classification of materials for the insulation of electrical machinery and apparatus in relation to their thermal stability in service.
5. IEC 76-1976 ; Power transformers.

1.4 SPECIFICATION

(A) Transformer*: Important specifications are : -

Volt-ampere (kVA or MVA); Voltage ratio (primary volt/secondary volt on no-load); Currents (primary & secondary); Number of phases; Frequency; Class (power/distribution); Percentage impedance; Load loss at 75-C; Connections–h.v. and l.v. windings; Maximum temperature-rise ; Per-cent-tappings; vector group reference (for three-phase transformers).

(B) Rotating Machines†: Important specifications are : –

(i) Direct current machine; Generator or Motor; Type of field excitation; Rated output power; Rated voltage ; Rated current : Speed; Field exciting voltage and current; Type of enclosure; Type of duty (for motor–continuous/ intermittent/short-time).

(ii) Alternating current machine : Generator or motor; Type (Induction/Synchronous/ Commutator); Frequency; Number of phases; Connection (Star/Delta); Rated output power (kW/MW); Rated voltage; Rated current; Speed; Type of rotor winding (for induction motor-squirrel-cage/slip-ring); Method of starting (for motor); Exciter rating (for synchronous machine); Type of duty; Type of enclosure; Type of cooling.

---

* IS 2026 – 1962 & 1180 – 1964
† IS 4722 – 1968

Additional informations furnished may be :–Short-circuit ratio and under-excited kVar/MVar (for synchronous generator); Overspeed on throwing off full-load with governor not in operation (for large power system generator); Breakway torque (for motor).

1.5 DESIGN AND CONSTRUCTIONAL ELEMENTS.

(A) Transformer: Important design and constructional elements are :–

(a) magnetic circuit, consisting of limb and yoke;
(b) electric circuit, consisting of low- and high-voltage windings;
(c) coil formers, on which the windings art wound; insulations–conductor, interwinding, and between windings and limb/yoke; spacers in core and winding to provide ducts for coolant;
(d) tank and auxiliaries, such as, heat exchanger, conservator, bushing, etc.

Limb and yoke consist of assembly of flat laminated steel sheets of suitable thickness. Laminations are assembled tight by compression to minimise vibration under magnetic repulsion forces, and noise. The laminations are separated from each other with thin layer of insulating film applied during the manufacturing process to reduce eddy-current losses. For large transformers, additional coating of thin insulation varnish or phosphate is normally required. The sheets are generally interleaved (art. 1.6.2) to avoid continuous break in the magnetic circuit.

The assembly of limb and yoke are so made that the top yoke is removable to admit the windings. Figure 1.2 shows some typical transformer frames.

The limb and yoke sections may be rectangular, square, or stepped (Figure 1.3) the number of steps in the yoke being generally less than that in the limb.

[*Note* : For large 3-phase transformers the five-limb pattern is commonly adopted since this reduces yoke depth and thus overall height of the transformer. This is necessary since height is usually restricted by transport considerations. Additional advantage of using this pattern is improved cooling of the yoke.]

Windings form the electric circuit and consist of conducting material–copper or aluminium, and insulation. In large transformers, capacitive protection rings and electrostatic shielding are provided for protection against voltage surges.

Figure 1.4 shows typical arrangement of l.v. and h.v.windings on the transformer limb. The l.v. winding is usually placed adjacent to the limb so that the insulation requirement between the winding and limb is less.

Figure 1.5 shows tank, tank-profile, conservator, heat exchanger and other auxiliaries. Tanks are normally of rectangular shape constructed from mild steel. Cylindrical shapes are often used for smaller sizes. For very large transformers, tanks are often made from aluminium with stiffeners to increase rigidity. The tank contains the core and winding assembly immersed in oil which serves as both dielectric and cooling medium. The cold oil enters at the bottom of the tank, extracts heat from winding and core, and its temperature rises. Hot oil moves upwards, flows into the heat exchanger and loses temperature. Conservator is an expansion chamber mounted either on the tank or on the heat exchanger so as to accomodate (i) increased volume of oil due to thermal expansion, and (ii) pressure–and gas-activated (Buchholtz) relay, an effective means of transformer protection.

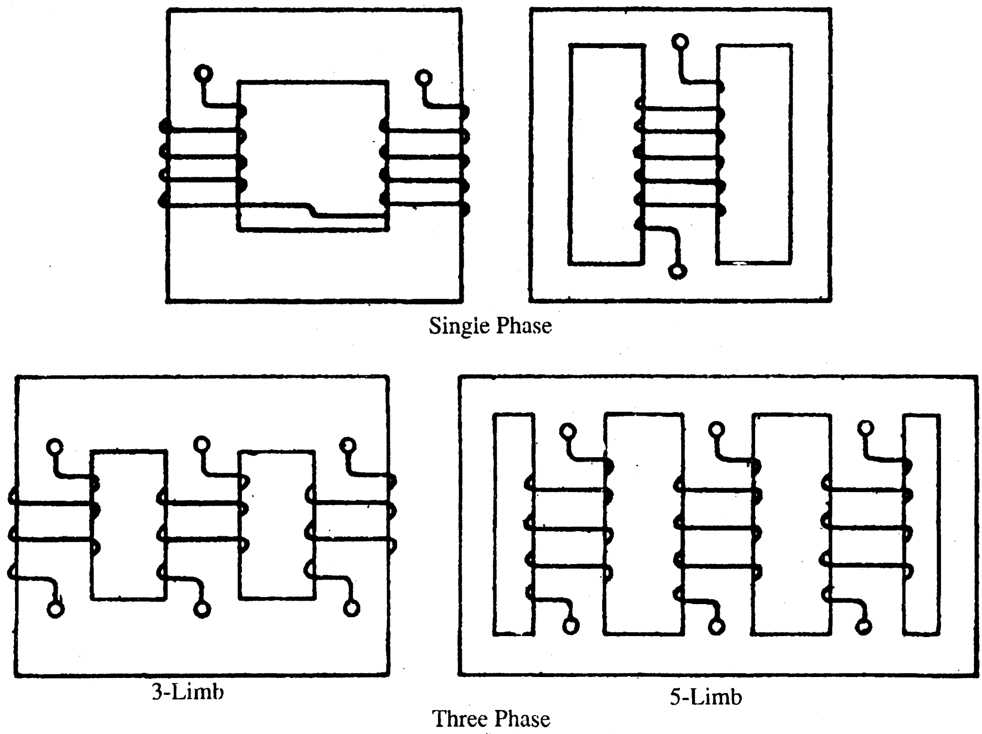


Figure 1.2 Transformer Frames.

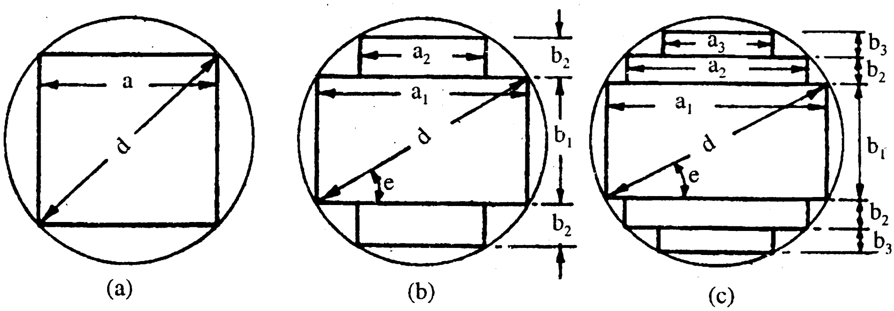


Figure 1.3 Tranfsormer core-sections, (a) square, (b) two-stepped, (c) three-stepped.

(B) *Rotating Machines*

Important constructional elements of a rotating machine (Fig 1.6) are :–

(a) stator and rotor cores separated by gap;
(b) stator and rotor windings with insulations;
(c) frame;
(d) shaft and bearings;
(e) commutator, slip-rings, brushes, brush-holder, brushgear, as and when required;

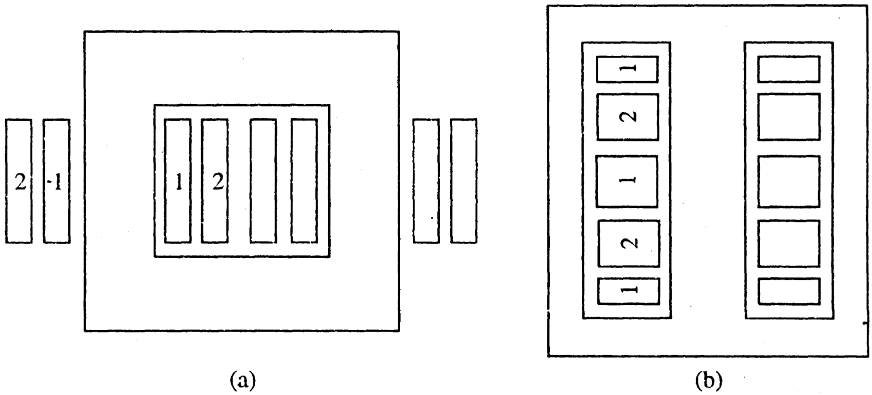


Figure 1.4 Winding arrangements, 1-l. v, 2-h.v. (a) concentric type, (b) sandwich type.

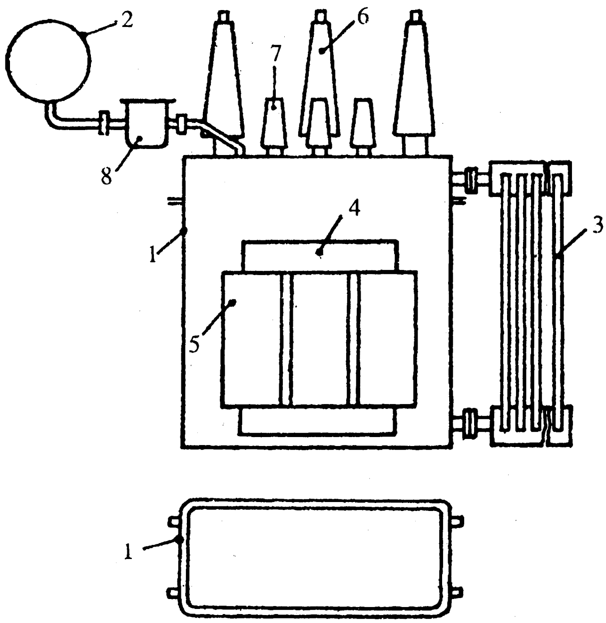


Figure 1.5 Transformer tank and auxiliaries, 1–tank, 2–conservator, 3–heat exchanger, 4–core, 5–winding., 6–h. v. bushing, 7–l. v. bushing, 8–Buchholz relay.

(f) cooling arrangement, such as, fan mounted on the shaft, provision of ventilating ducts, etc.

In d. c. machine, the armature is on the rotor consisting of an assembly of laminations 0.4 to 0.45 mm. thick insulated from each other by thin coating of varnish or paper. There are slots uniformly around the armature periphery to house the armature winding. The field poles, generally unlaminated and made of forged steel are bolted to the stator frame. In almost all d.c. machines the magnetic circuit completes through the frame made of cast steel or rolled steel

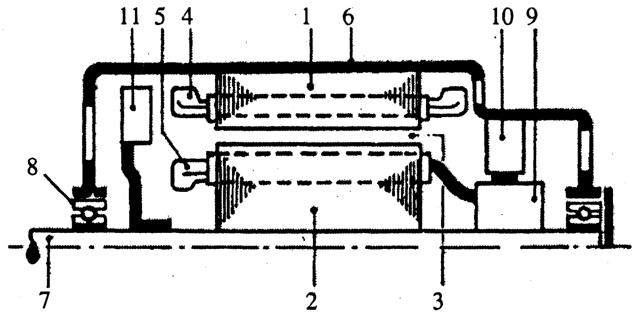


Figure 1.6 Rotating machines-constructional elements, 1–stator core, 2–rotor core, 3–gap, 4–stator winding, 5–rotor winding, 6–frame, 7–shaft, 8–bearing, 9–commutator, 10–brush and brush–gear, 11–fan.

(Figure 1.7). The pole-shoes are laminated and fixed to the pole-core by counter-shunk screws. In very small machines, the entire stator is usually laminated-yoke, poles aud shoes forming part, of the same lamination (Figure 1.8), 1 mm. to 1.5 mm. thick.

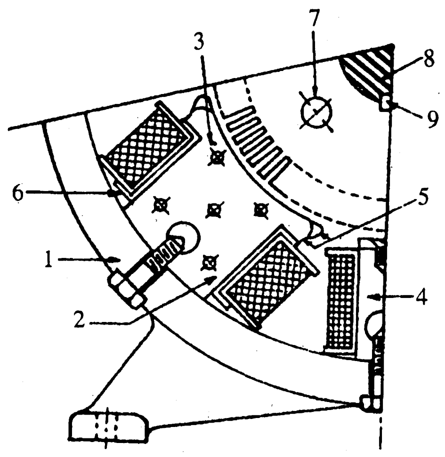


Figure 1.7 D.C. machine, 1–yoke, 2–pole core, 3–pole shoe, 4–interpole, 5–interleaved assembly, 6–insulated shield, 7–axial duct, 8–shaft.

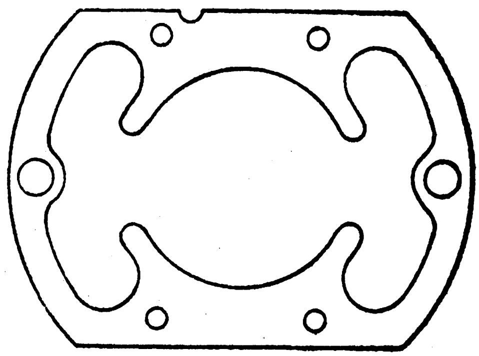


Figure 1.8 Stator lamination–small d.c. machine.

In synchronous and induction machines, the armature core generally forms the stator. The core is laminated with slots placed uniformly around the inner periphery to house the armature, winding.

The rotor of a synchronous machine can be either salient-pole or non-salient pole type (Table 1.1). Except the water-wheel generator, all other classes are horizontal-shaft type, whereas waterwheel generators are generally vertical shaft type. Thus, waterwheel generators require thrust- and guide-bearings.

Table 1.1 Classification of synchronous Machines

Class	Type	Maximum rating to – date	Speed range
Turbo-generator	Non-salient pole	1000 MW	upto 3600 rpm.
Water-wheel generator	Salient-pole	750 MW	90 to 1000 rpm.
Engine-driven generator	Salient-pole	20 MW (Diesel engine driven)	upto 1500 rpm.
		50 MW (Gas turbine driven)	upto 5000 rpm.
Motor	Salient/non-salient pole		
Compensator	Salient /non-salient	100 MVAr	upto 1000 rpm.

In turbo-generators, large centrifugal force due to high peripheral speed necessitates the use of rotor made of massive steel forging. The field winding is distributed in slots which are thus deep and are milled from the rotor cylinder. (Figure 1.9)

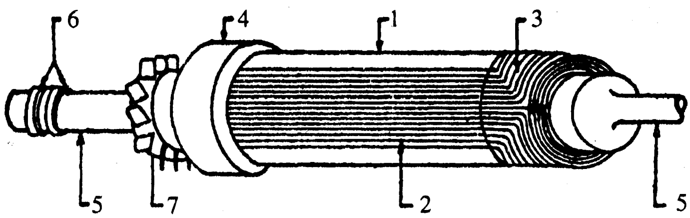


Figure 1.9 Turbogenerator rotor, 1–rotor body, 2–winding in slots, 3–rotor overhang, 4–retaining ring, 5–journal, 6–slip-rings, 7–blower.

In a salient-pole machine the poles are formed by an assembly of thin steel sheets clamped between heavy end-plates. The poles are suitably bolted to the rotor body or may be dovetailed. The rotor body may be forged or made up of discs shrunk on to the shaft or may be fabricated from a cast steel spider mounted oti to the shaft.

For an induction motor, the rotor body is fully laminated with slots uniformly punched around the rotor periphery. For smaller sizes the rotor lamination assembly is keyed to the shaft and suitably clamped. For larger sizes, the core is held on a fabricated shaft.

In magnetic circuit calculation, gap forms the most important element. Flux distribution in the gap is important and in salient-pole machines, the gap length at the pole tip is increased to avoid excessive flux distortion.

The electric circuit comprises the stator and rotor windings. The armature windings in rotating machines and the rotor winding of slip-ring induction motors are usually of copper placed in slots with suitable insulations on the conductor, between turns and between the coils and the armature core. The armature windings are generally of double layers. The field exciting windings on salient poles are concentrated type, generally wound on edge (Figure 5.2) on coil formers mounted suitably on the pole body. The squirrel-cage winding of an induction motor are formed by copper or aluminium bars placed in rotor slots without any insulation. The bars are shortcircuited at each end by endrings welded or brazed to the bars. (Figure 1.10) For small motors, rotor bars and endrings are of aluminium formed by integral die-casting.

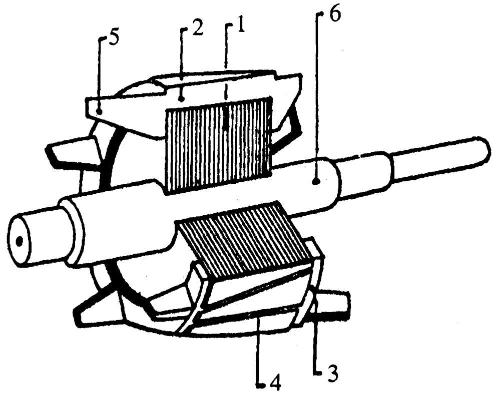


Figure 1.10 Squirrel-cage rotor. 1–lamination, 2–bar section, 3–end ring, 4–skewed bar, 5–buikt-in fan 6–shaft.

The vast majority of rotating machines are air-cooled. The cooling system is closely associated with ventilation schemes and enclosures of the machines, and the most common system for low and medium-size machines is by using fan mounted on the shaft and ventilating ducts–radial and axial. In large turbogenerators, hydrogen cooling and water cooling are being used with considerable advantage (chapter 2.).

1.6 MATERIALS

1.6.1 CONDUCTING MATERIALS

Copper is the most important conducting material used in electrical machines. However, because existing copper deposits are fast exhausting and the price of copper fluctuates widely, aluminium is progressively replacing copper in many applications. Important points of comparison between copper and aluminium are given in Table 1.2.

Table 1.2

SI. No.	Item	Copper	Aluminium (times that of copper)
1.	Resistivity* (ohm. mm^2. m^{-1})	0.0214	1.64
2.	Specific weight (kg. mm^{-2}, m^{-1})	8.89	0.33
3.	Thermal conductivity (W. m^{-1}. °C^{-1})	350	0.57
4.	Specific heat (J. Kg.$^{-1}$ °C^{-1})	400	2.3
5.	Coefficient of linear expansion at 20°C per degree celsius	$17\times10^{=16}$	1.35
6.	Melting point (°C)	1083	0.6

* at 75°C temperature.

[*Note* : (1) Specific resistance of aluminium is 1.64 times that of copper Thus, for the same i^2r- loss a general purpose standard industrial motor or generator will have roughly a reduction of power rating by 22 percent if wound with aluminium*.

(2) The most important advantage of using aluminium is that it is approximately 3.3 times lighter than copper ; and aluminium being cheaper (in rupees per tonne) results in large reduction in the cost of conductors.

However, in certain cases, this reduction may be offset by the increased volume of windings needing increased amount for insulation and labour. For example, for the same temperature-rise of stator and rotor, and for the same number and width of stator slots, the slot depth with aluminium is about 1.20 times that with copper. This means increased eddy-current loss (by approximately 1.62 times) and also an increased leakage reactance.

(3) Use of aluminium strip for l.v. winding, and in some cases, of aluminium foil for the h.v. windings of distribution transformers are popular in USA and certain European countries. Problems concerning manufacturing methods and jointing have been solved.*

One important advantage of using aluminium for transformers is its immunity to attack by transformer oil, and oil in aluminium-wound transformers deteriorate more slowly than in copper-wound ones.]

1.6.1.1 Superconducting Material

Superconductivity, a phenomenon discovered by Dutch Scientist Onnee, in 1911 exhibits the property of certain elements and compounds that their resistivity sharply decreases to practically zero value when, (i) temperature is brought down below 'transition'temperature; (ii) the magnetic field external to the super conductor or created by the current flowing in it is below a certain value.

For example, Niobium-tin compound (Nb_3Sn) has a transition temperature of 18.1°K and its critical flux-density (above which the super conductivity ceases to exist) is about 20 Tesla. Some important superconducting material and their transition temperatures are given in Table 1.3. Again, in a ring of superconducting material, the current once induced will continue to flow unchanged without additional power being supplied.

That is, with a superconductor under cryogenic conditions, a very strong magnetic field can be obtained with hardly any power consumed.

Superconductor in transformer

The use of superconductors in transformers and rotating machines depends on the comparative gain in reduction of I^2R- losses against the cost for provision of cryogenic conditions. A study on the use of superconducting transformer winding* revealed that in a 570 MVA transformer,

* $R_{al}/R_{cu} = 1.64$; $I^2_{al} R_{al} = I^2_{cu} R_{cu}$; $I_{al}/I_{cu} = (R_{cu}/R_{al})^{1/2}$
$P_{al}/P_{cu} = (E_t.I_{al})/(E_t.I_{cu}) = (R_{cu}/R_{al})^{1/2} = (1/1.64)^{1/2} = 0.78$

* T. Pelican : "Modern Distribution Transformers with aluminium foil winding", Brown Bovari Review, vol. 54 (7), 1967, pp. 376-381.
M. McCormick : "Aluminium foil transformer coils", Electrical Review, vol. 183, 1968; pp. 452-454.

* K. J. H. Wilkinson, "Superconductive windings in Power Transformers", Proceedings, IEE, vol. 110, 1963, p. 2271.

Table 1.3 Superconducting Element and Compound

Element	Transition temperature (°K)
Titanium	0.49
Zinc	0.82
Aluminium	1.20
Tin	3.73
Mercury	4.16
Vanadium	5.1
Lead	7.22
Niobium	8.0
Compound	
Nb_2Zr	10.8
V_3Si	17.1
Nb_3Al	18.0
Nb_3Sn	18.1

(i) a superconducting winding will have to operate at a leakage flux-density of 3.5 T;
(ii) I^2R- loss of 3 MW can be a eliminated;
(iii) core loss can be reduced by 50 KW by decreasing tho core mass from 100 to 65 Mg.
(iv) refrigeration power requirement will be about 0.5 MW.
(v) cost of development and of refrigeration plant might balance out the saving obtained in the reduction of losses.

That is, the use of superconducting transformer winding is not yet economically viable.

Superconductor in large turbogenerator

A study with respect to the feasibility of using superconducting materials for the rotor winding of a 660 MW turbogenerator has been made by Lorch†. Since the stator current is alternating, superconductors cannot be used for the stator winding. For the rotor, the study is based on the following recommendations :–

(i) The rotor body is a hollow cylinder of glass reinforced epoxy resin with steel ends;
[Note : A normal forged steel rotor will be of no advantage at the high flux-density developed by superconductivity. Moreover, such a rotor will conduct heat from the bearing which is a disadvantage since cryogenic condition is to be set up.]
(ii) Slots are provided on the rotor cylinder in which superconducting winding wrapped in glass-epoxy resin is placed.
(iii) The coolant for the coils is helium entering and leaving the rotor axially by which the temperature of the coils can be brought down to 5°K.
(iv) A thin copper cylinder is fitted to the rotor and is thermally insulated from it by a pealed stainless steel vacuum enclosure maintained at a temperature between 80 and 135°K. The copper cylinder is required to act as a screen to protect the rotor from harmful a.c. magnetic fields.

† Lorch, H. O., "Feasibility of Turbogenerator with superconducting rotor and conventional stator", Proceedings IEE, vol. 120; 1973, p. 221.

(v) A stationary system of cylinders within the stator bore with liquid nitrogen flowing through it forms a cold screen at about 77°K.

(vi) The gap between the stationary and rotating members is filled with hydrogen at 0.1 mm mercury pressure to reduce the windage loss.

The above recommendations if implemented, will result in,

(a) a very low excitation requirement, The exciter rating would be of the order of 2.5 MW for a few seconds only as the initial excitation to establish the required magnetic field energy.

(b) a peak density as high as 5 Tesla, at which the stator core must be nonmagnetic.

However, as in the case of transformer, the use of superconductors in large power system generators depend on cost effectiveness, and it has teen envisaged that such a step will be economically viable for generators above 1000 MW rating. A designer's conception of synchronous generator with superconducting field winding is shown in Figure 1.11.

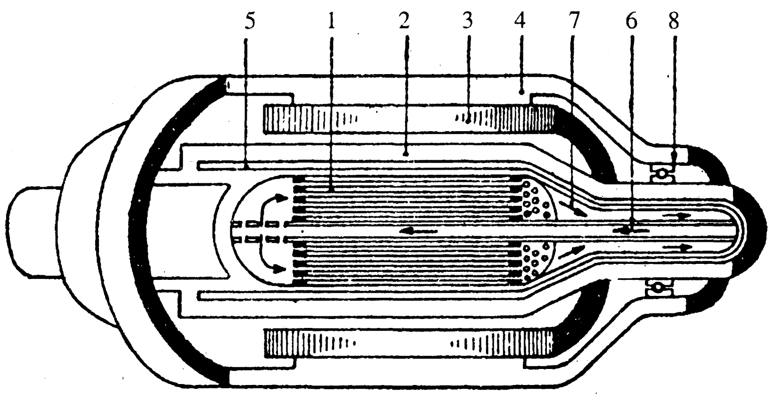


Figure 1.11 Synchronous generator with superconducting winding, 1–Superconducting field winding, 2–rotor body, 3–stator core, 4–iron shielding, 5–vacuum insulation, 6–helium inlet, 7–helium outlet, 8–bearing.

1.6.1.2 For direct-cooled synchronous machines, stator conductors are made hollow to allow the coolant to flow through the conductors and extract heat directly from the source. Hard-drawn copper tubes or electrolytic copper with about 4 per cent silver is used.

1.6.2 Magnetic Material

The electric sheet steel is the most, important core material for electrical machines. Addition of silicon, 1.8 to 3 per cent to the iron

(i) increases the resistivity in steel almost in direct proportion to the silicon content (Figure 1.12);

(ii) reduces hysteresis and eddy-current losses;

(iii) increases magnetic permeability of steel in weaker magnetic fields, but reduces it in stronger fields;

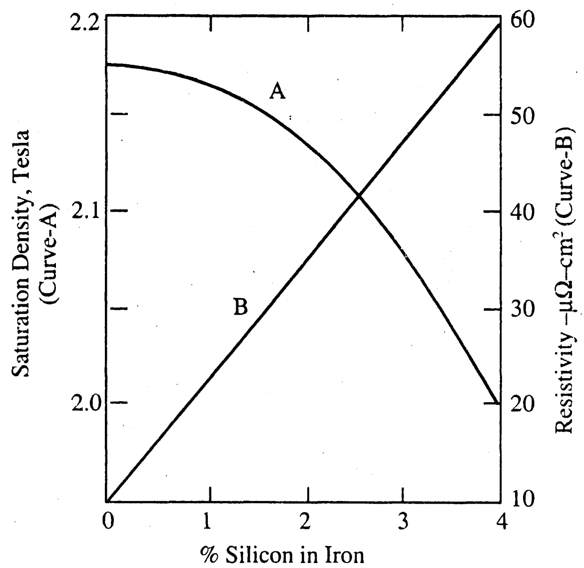


Figure 1.12 Effect of addition of silicon to iron.

(iv) abates 'aging'* of steel;

(v) impairs certain mechanical properties of steel, specially its machinability.

Electric sheet steel is mainly of two types :–

(1) Hot rolled (HRS);

(2) Cold-rolled Oriented (CROS).

In contrast to hot-rolled steel, CROS sheets have improved magnetic properties (lower specific loss and magnetic field intensity at working flux-density), when magnetic flux is directed along the direction of rolling. Due to rolling under cold conditions and subsequent annealing in an atmosphere of hydrogen, iron crystals are made to prevail in the direction of rolling thereby imparting to the steel a sharply defined anisotropy. This property has led to its successful use in transformers and lately, in certain rotating machines. Considerable reduction in core dimension and weight are achieved by use of CROS, i.e. by 20 to 25 per cent in power transformers and about 40 percent in radio transformers.

Table 1.4 and Figure 1.13 give a comparison between the two types. HRS and CROS sheets are available in many grades.

Hot-rolled sheets suffer from an important imperfection in comparison with cold-rolled sheets relating to the variation of thickness. For example, a typical sample of HRS sheet –1.0 m × 0.30 m. having a nominal thickness of 0.33 mm. has a thickness variation from 0,03 to 0.0387 mm. Such imperfection results in imperfect assembly of core with alternatively tight and slack zones.

In contrast to above, cold-rolled sheets of nominal thickness 0.33 mm. show a variation of about 0.0123 mm. i.e. less than one-third of that of hot-rolled sheets.

* 'Aging' is expressed by increased iron losses with time.

Table 1.4 Comparison of Magnetic Sheets.

	Hot-rolled	**Cold-rolled oriented**
Sheet thickness	0.35 mm.	0.33 mm.
Maximum working flux-density, Tesla	1.1–1.15	1.6–1.85 in the direction of rolling.
Specific loss,* W. cm^{-3}	0.0249	0.0114 in the direction of roll; 0.0256 at right angles to the direction of roll.
Ampere-turn per cm*	20	1.3 in the direction of roll. 18.1 at right angles to the direction of roll.
Density gm. cm^{-3}	7.55	7.65
Stacking factor	0.9–0.95	0.95–0.98

* at 1.45 Tesla and 50 Hz.

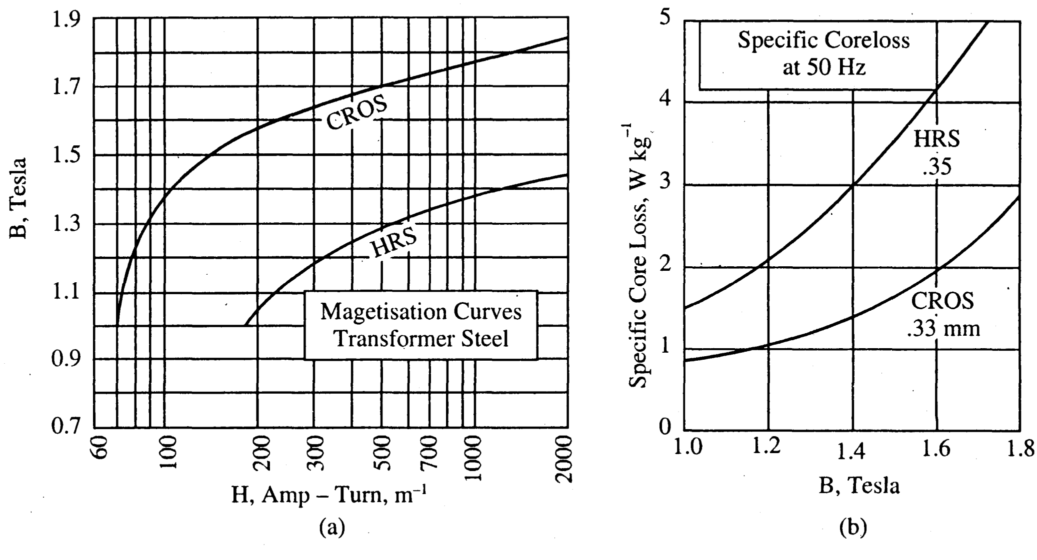


Figure 1.13 Characteristic curves for HRS and CROS.

[*Note* : The working of HRS sheets into proper shapes and sizes is done with the help of power guillotines and multiple presses. With CROS such process impairs the magnetic properties and this can be somewhat avoided if sheets are given stress-relief anneal at a temperature of about 800°C in an inert atmosphere so as to avoid oxidation and carbon contamination. For HRS, a thin coating of varnish or kaolin serves as surface insulation so that eddy-currents are checked. Such thin coating is normally not necessary for CROS as the phosphate-basic coating used during the annealing process serves as an insulation. However, in transformers above 10 MVA, varnish insulation is used.]

CROS sheet is costlier than the HRS, involves complicated process of construction and assembly of core, and improved method of machining the laminations. Care must be taken with respect to the direction of rolling during the assembly of laminations as both specific loss and ampere-turn per cm. increases rapidly with the direction of flux-path away from the direction of rolling (Figure 1.14).

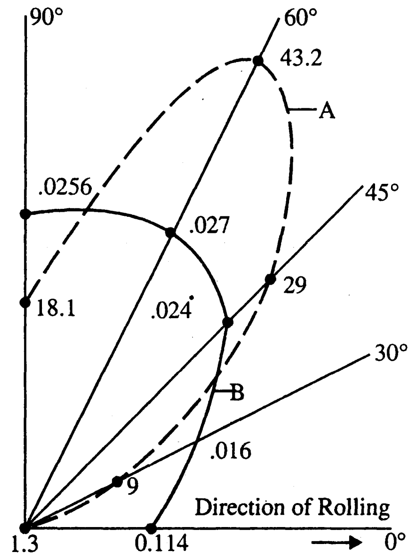


Figure 1.14 Effect of direction of rolling. A - amp - turn/cm, B - Sp. loss.

CROS in transformer Figure 1.15 (a) shows the assembly and interleaving of hot-rolled laminations in three-phase core of a tranformer. Such method of assembly if used with CROS laminations will give rise to increased losses at the corners of the assembly since the flux bends at the corners (Figure 1.15 b-i) and loss increases as the direction of flux-path is away from the direction of rolling. A corner-cut as in Figure 1.15 (b-ii) will definitely improve the use of CROS but this leads to continuous break at the corners. Mitre joints (Figure 1.15 b-iii & viv) are used to overcome this problem. Further, with mitre, specific iron loss is lesser than that with square-cut corners since uneven flux-distribution at the joints, bolt-holes, etc. are less pronounced with mitre. For transformers in which tbe strip width required is larger than the available standard, the core is splitted up into two sections connected by bridges for effective maintenance of flux-path in the central limb (Figure 1.15 b-v).

CROS in rotating machines In rotating machines such as induction and synchronous, the direction of flux-path in teeth and core below teeth is as shown in Figure 1.16. Efficient use of CROS in armature core of synchronous machine, and stator and rotor core of induction motor is difficult to achieve because,

(i) The flux-path is radial along the teeth and circumferential in the core below teeth. Thus, if the direction of orientation is made somewhat radial, specific loss in teeth will be reduced by about (0.0114/0.0249) = 46 percent, whereas there will be an increase in specific loss in the core below teeth by about (0.0256/ 0.0249) = 103 percent.

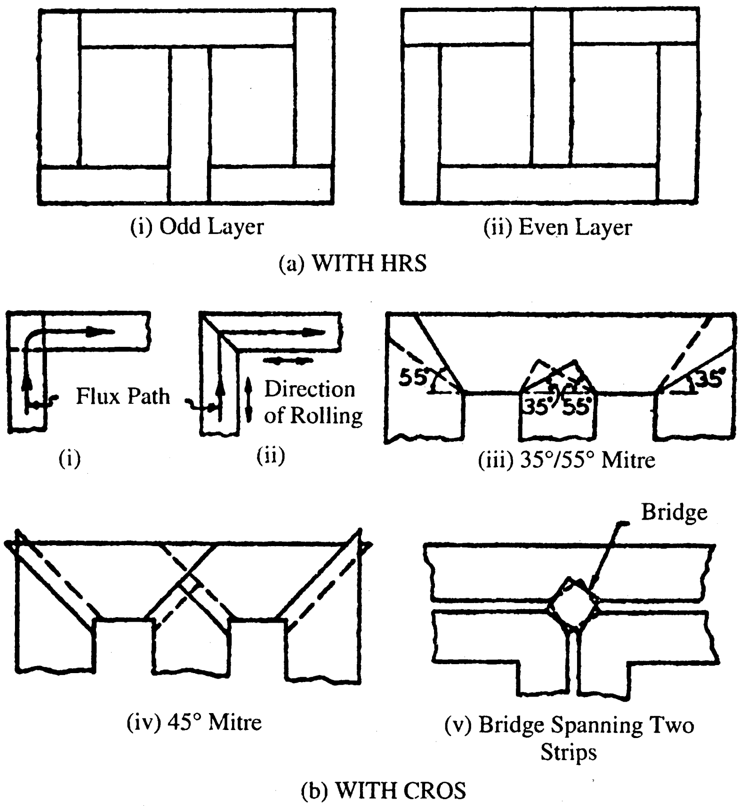


Figure 1.15 Assembly and interleaving of transformer laminations.

(ii) Axis of one tooth makes angle with that of the next, and if the direction of rolling is made to coincide with the axis of any one tooth, it will be at some angles with the other. That is, the reduction in specific loss will vary from one tooth to another.

(iii) In small induction and synchronous machines, the complete armature core is stamped out of a single sheet (Figure 1.16) and use of CROS sheets of a particular directional rolling will result in reduction of losses in certain regions and increase in other, and net result will be of disadvantage.

From the above discussion, it can be concluded that the use of CROS in rotating machines depends on its judicious use in consideration of direction of rolling. For example, for machines with large diameter and large number of poles (as in water-wheel generator) variation of angle between the axis of one tooth and that of the next is not pronounced and use of CROS with segmental core laminations and radial direction of grain oiientation (Figure 1.17a) has proved to be of definite advantage*. On the other hand, in large induction motors (2, 4 and 6 poles) and in 2-pole turbogenerators, the bulk of the core loss is in the core below teeth and segmental

* J. H. Walker : Large A. C. Machines. Published by Bharat Heavy Electrical Limited.

core with rolling direction tangential to the bore-circle (Figure 1.17b) has often given rise to an overall reduction in core losses.

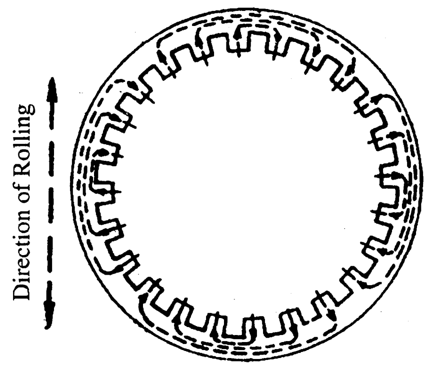


Figure 1.16 A complete stator lamination.

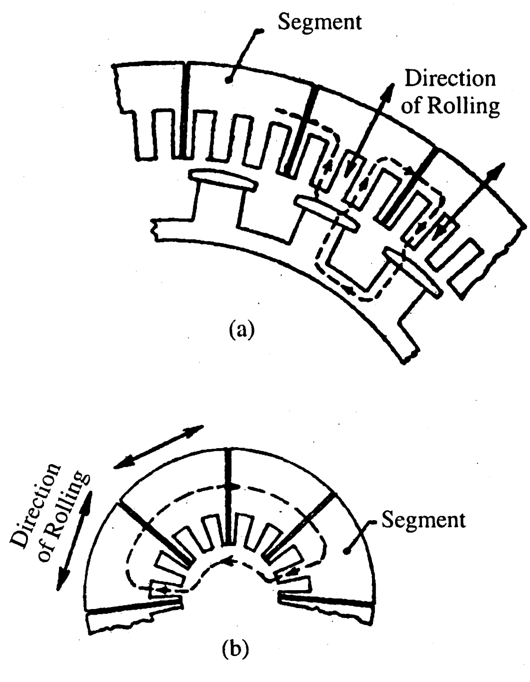


Figure 1.17 Segmental-core lamination-assembly. (a) water-wheel generator, (b) turbogenerator and induction motor.

1.6.2.1 *Strip-wound transformer core using CROS*

It has been shown above that if the flux is made to 'flow' in the direction of orientation of grains in CROS sheets high permeability and low hysteresis can be achieved. Use of strip-wound cores manufactured by winding the material in the form of continuous strip on suitable mandrels, allows the flux to travel in the direction of orientation. Such winding operation imposes mechanical stress on the material which can be removed by annealing the formed cores in a controlled atmosphere.

Strip-wound cores have the advantage of having minimum core loss and is widely used in small distribution transformers. Use in power transformers upto 3.3 MVA has also been reported† Important disadvantage is the requirement of expensive plant for annealing the entire formed core. Further, as evident from Figures 1.18 (a-ii) & (b), flux cannot readily transfer from one loop to another ; and since, in order to develop sinusoidal flux in each winding individual loop-fluxes develop large 3rd harmonic flux, there is an overall increase in core losses which can be as high as 33 percent.

1.6.3. Insulating Materials*

There are quite a large variety of insulating materials that are used for the insulation of current-carrying parts in electrical machines. Some common insulating materials are :–

paper, pressphan, card board, empire cloth, mica, asbestos, micanite, transformer oil, varnish, etc.

The fundamental requirement for good insulating material is *high dielectric strength.*

Again, it is necessary that solid insulation shall provide a means of physically separating the conducting part. This necessitates that the insulation assemblies must have the mechanical properties to withstand compression, tension, flexing, and abrasion to the extent depending upon each type of machine design and application.

The third important requirement is *heat transfer*. Electrical machines generate heat in their normal operation, and since insulation comes into contact with heated parts its response to high temperature and its capacity to conduct heat are its important properties.

Life of an electrical apparatus is determined by the life of its insulation which apart from mechanical damage, is dependent on the temperature at which it is made to work. The complicated nature of heat generation, heat flow and heat dissipation in electrical apparatus leads to the existence of thermal gradients within the coil structure and is esential for a designer to see that the hottest spot in the coil-structure does not exceed the critical temperature for the insulation used.

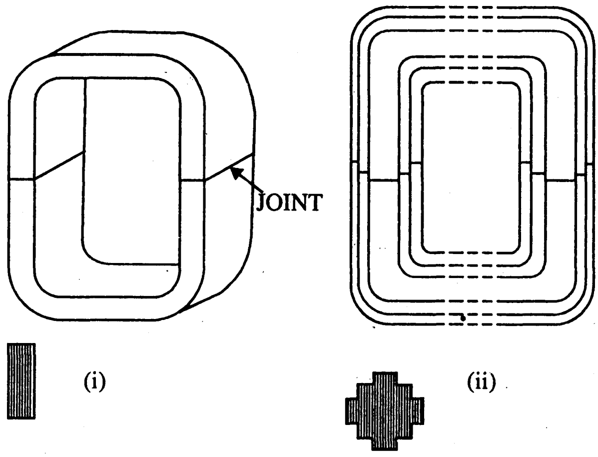
Thus in considering the applications of insulating materials, recent progress has placed major emphasis on the temperature-limitations of their use. With increased applications of synthetic insulating materials, this problem has become important.

Again, efficiency in use i.e. reduction in size for the same rating and reduction in cost demand operation of a machine at higher temperature and higher voltage, thereby demanding the use of insulating materials to the practical limits of their temperature and voltage.

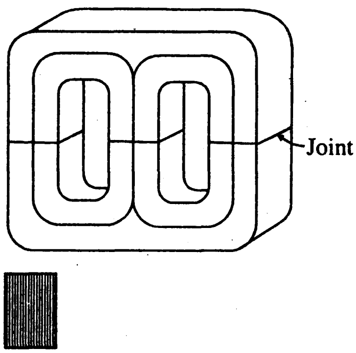
Table 1.5 gives the thermal classification of insulating materials as adopted by the International Electro-technical Commission (IEC 85–1957).

† Gordy, T. D. and Sotnervillc, G. : Single-phase Power Transformer Formed cores, Transaction AIEE, Vol. 69, 1950, p. 1384.

* F. M. Clark, Insulating Materials for Design and Engineering Practice. John Wiley.



(a) Cut 'C' Core



(b) Cut 'E' Core

Figure 1.18 Strip-wound cores.

Table 1.5 Thermal Classification of insulating materials.

Class	Limiting working temperature °C	Typical materials
Y	90	*Organic, fibre materials on cellulose base*, such as, paper, pressboard, cotton etc.; natural silk (not impregnated), ther mo-plastics.
A	105	*Fibre materials of class Y impregnated* with lacquers (varnishes) or compounds, or dipped in liquid dielectrics ; enamel of wires coated with varnishes and phenolic resins.
E	120	*Enamelled wire insulations on base of* polyvylformal, poly-urethane and epoky resins, moulding powder plastics on phenolic formaldehyde, etc.
B	130	*Inorganic material* (such as, mica, glass, asbestos) *impregnated* or glued with organic binder possessing ordinary heat resistance (on bases of drying oils, bitumen, shellac, bakelite etc.)

F	155	*Inorganic material impregnated* or glued together with epoxy or other varnish of high resistance.
H	180	Mica, glass, asbestos *with silicon binder, silicon resin.*
C	Above 180	*Inorganic materials* (mica, porcelain, glass, mycalex, etc.) *not impregnated with organic material but with inorganic binding material,* such as, glass or cement. Heat resistant micanite, Teflon fall under this category.

[*Note* : (1) Impregnation replaces the air between the fibres of the insulating material. Impregnating material must have good insulating properties and must neither flow at normal temperature nor deteriorate under prolonged action of heat.

(2) Insulating materials are never used singly, but in combination which promotes their usability at high temperatures satisfying the three important requirements mentioned above.]

Typical use of insulation in electrical machines are illustrated in Figure 1.19.

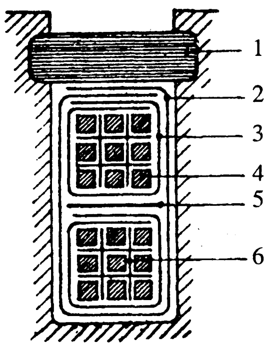


Figure 1.19 Typical insulation in d.c. armature slot. 1–wedge, 2–paper slot-lining, 3–paper – varnished cambric, 4–d.c.c. conductor, 5,6–paper separator.

1.7 LOSSES IN ELECTRICAL MACHINES

Study of various losses occuring in electrical machines is important as the losses determine the heating, temperature-rise and efficiency of the machine. The localised losses in a machine chiefly determine the temperature-rise whereas the total losses determine the efficiency.

1.7.1 Variation of Losses with Load

The total losses W_L can often be expressed as a function of the power-rating P by an equation of the form,

$$W_L = a + b\,P^2 \tag{1.1}$$

a and b being constants (Figure 1.20)

Equation (1.1) is practically valid for machines with somewhat constant flux (transformer) or, machines with somewhat constant flux and speed (synchronous machines and induction

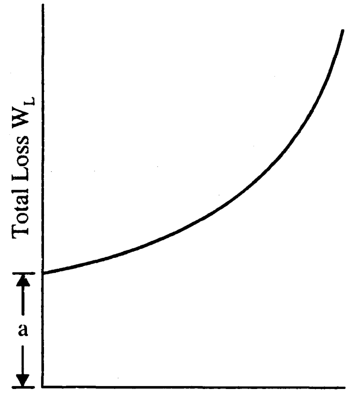


Figure 1.20 Variation of total loss.

motor), 'a' represents the constant losses (iron, friction and windage) and the second term, the variable losses which are proportional to the square of the load.

1.7.2 Electrical Losses

(i) I^2R- losses in a coil due to the flow of uniform electric current in it. Such losses depend on the temperatures of conductors which affect resistivity. It is customary to use 75°C as the normal operating temperature of a machine and state the losses corresponding to this reference value.

For a coil of T-turns and mean length of turn s metre wound with conductor of section area a metre^2, and resistivity ρ ohm. m, the coil resistance is given by,

$$R = \rho\, T\, s\, /\, a \text{ ohm.} \tag{1.2}$$

Specific i^2r-loss, defined as the I^2R-loss watt per kg. of conductor material, is given by,

$$W_r = J^2\rho/G_c \text{ watt. kg}^{-1} \tag{1.3}$$

where, J amp.m^{-2} is the current-density, and G_c kg.m^{-3}, the specific weight of conductor material.

From Table 1.2, at 75°C, for copper, ρ = 0.0214 ohm.mm^2.m^{-1} and G_c = 8.89 g.mm^{-2} .m^{-1}

$$W_r = 2.41 \times 10^{-12} J^2 \text{ W.kg}^{-1} \tag{1.3a}$$

and similarly, for aluminium,

$$W_r = 11.84 \times 10^{-12} J^2 \text{ W.kg}^{-1} \tag{1.3b}$$

[*Note :* The resistivity of aluminium being about 1.6 times and the density being about 1/3rd that of copper, for equal length of a coil and losses, aluminium conductor-section will be about 1.6 times that of copper. This means increased volume of aluminium required. But the weight of aluminium will be only 1/2 that of copper. For a coil on the rotor of a machine, this means lesser centrifugal stress.]

(ii) I^2R- *loss due to circulating current* may occur when two or more coils in a machine are in parallel and have different voltages induced in them.

Consider a d.c. circuit comprising two similar coils 1 and 2 in parallel each having a resistance R but slightly different voltages e_1 and e_2 induced in them. With currents i_1 and i_2 flowing in the coils (Figure 1.21) and e, the common p.d.,

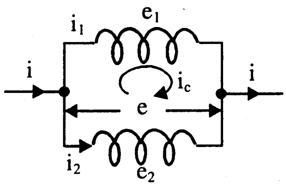


Figure 1.21 Pertaining circulating current in coils.

$$i = i_1 + i_2$$
$$e = e_1 - Ri_1$$
$$= e_2 - Ri_2$$

Defining, average e.m.f. $e_{av} = \frac{1}{2}(e_1 + e_2)$.

$$e = e_{av} - \frac{1}{2}Ri$$

$$i_1 = \frac{1}{R}(e_1 - e_{av}) + \frac{1}{2}i$$

and the circulating current,

$$i_c = \frac{1}{R}(e_1 - e_{av}) \tag{1.4}$$

Equation (1.4) shows that a circulating current is superposed on the normal curent can be very large if R is very small. It can cause losses which at first sight seem to be inexplicable since they correspond to a current which does not appear in the main circuit.

(iii) I^2R-*loss due to a current varying* according to a given law.

For any current $i = f(t)$ in a coil of resistance R in time T sec, the losses are expressed in terms of effective current I_{rms} which would produce the same heating in time T as the varying current. That is

$$I_{rms}^2 = \frac{1}{T}\int_0^T i^2 dt \tag{1.5}$$

The following two cases may be considered :-

Case I : i varying linearly from I_1 to I_2 in time T sec. (Figure 1.22a).

$$i = \frac{1}{T}(I_2 - I_1)t + I_1, \qquad 0 \le i \le T$$

giving, $$I_{rms} = \left[\frac{1}{3}(I^2{}_1 + I^2{}_2 + I_1.I_2)\right]^{1/2} \quad (1.7)$$

Case II : *i* varying as in Figure (1.22b).

$$i = I_1, 0 \le t \le T' \quad (1.7)$$

giving, $$I_{rms} = I_1 \cdot (T'/T)$$

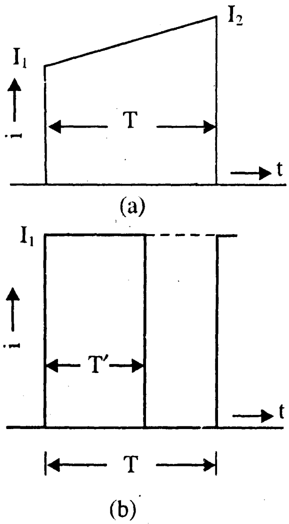


Figure 1.22 Pertaining I²R-loss due to varying current.

(iv) I²R*–loss due to superimposed currents.*

Case I : A coil carrying a direct current I_1 and a sinusoidal alternating current I_2 rms.,

$$i = I_1 + \sqrt{2}I_2 \sin \omega_s t$$

whence $$I_{rms} = (I^2{}_1 + I^2{}_2)^{1/2} \quad (1.8)$$

The total I²R- loss is thus the sum of the losses due to the direct current and the alternating current flowing independently.

Case II : A coil carrying a non-sinusoidal alternating current. Resolving the non-sinusoidal current into its fundamental and harmonic components,

$$i = \sqrt{2}I_1 \sin \omega_s t + \sqrt{2}I_2 \sin(2\omega_s t + \phi_1) + \sqrt{2}\, I_3 \sin(2\omega_s t + \phi_2) + \cdots$$

whence, $$I_{rms} = \left(I_1^2 + I_2^2 + I_3^2 + ...\right)^{1/2} \quad (1.9)$$

That is, the total I²R- loss is the sum of the losses due to each component current flowing independently.

(v) *Eddy-current loss in conductors*

Eddy-currents induced in conductors placed in an alternating magnetic field result in losses.

In an isolated conductor, parasitic eddy-currents are induced due to its own field (developed as a result of current flowing through the conductor). The phenomenon, known as *skin effect* results in conductor current flowing more readily in the outer layers of the conductor.

In machines and transformers however, the conductors are not isolated (e.g. in machines, the conductors are embedded in slots), and the proximity of ferromagnetic material intensifies the effects of alternating leakage fluxes arid causes increased eddy-current losses. Determination of eddy-current loss in such cases is complex because of complicated nature of leakage paths. However, simplified expressions could be developed for certain cases, making suitable assumptions, as indicate below.

Case I : Single conductor in slot in an electrical machine.

Assuming the iron path of the leakage flux having infinite permeability, the flux-paths within the slots can be considered to be straight lines (Figure 1.23a).

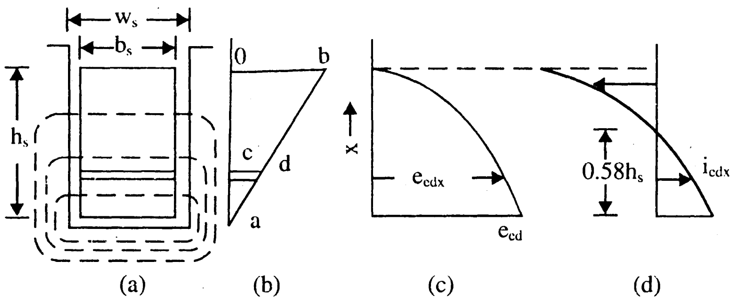


Figure 1.23 Eddy-current in single conductor in a slot.

For simplicity, consider a parallel-sided open slot with the conductor carrying a uniformly distributed current of maximum value i_m, alternating at a frequency *f*.

The mmf is zero at the bottom a of the conductor increasing uniformly to a value F at the top b (Figure 1.23b). At the top, the flux-density $B_b = \mu_o i_m/w_s$. so that the total flux per metre length of the conductor,

$$\doteq \text{area } oab = \frac{1}{2}\mu_o i_m \, h_s / w_s.$$

Considering an elemental lamina dx and noting that the lamina is linked by the flux above it, which is equal to the area *obdc*,

$$= \frac{1}{2}(h_s - x) \cdot (ob + cd)$$

$$= \frac{1}{2}(h_s - x)\left(\mu_o \frac{i_m}{w_s} + \frac{x}{h_s}\mu_o \frac{i_m}{w_s}\right)$$

$$= \frac{1}{2}\mu_o \frac{i_m}{w_s}\left(h_s - \frac{x^2}{h_s}\right),.$$

the maximum value of eddy-voltage induced in the lamina,

$$e_{edx} = 2\pi f \frac{1}{2} \mu_o \frac{i_m}{w_s} \left(h_s - \frac{x^2}{h_s} \right)$$

$$= \pi f \mu_o \frac{i_m}{w_s} \left(h_s - \frac{x^2}{h_s} \right) \qquad (1.10)$$

A plot of eddy-voltage eedx against x as obtained from equation (1.10) is shown in Figure 1.23(c). The average value of the eddy-voltage,

$$e_{edav} = \frac{1}{h_s} \int_o^{hs} \pi f \mu_o \frac{i_m}{w_s} \left(h_s - \frac{x^2}{h_s} \right) dx$$

$$= \frac{2}{3} \pi f \mu_o \frac{i_m}{w_s} h_s \qquad (1.11)$$

which occurs at $x = x_1$ where, $h_s - \frac{x_1^2}{h_s} = \frac{2}{3} h_s$

That is, $x_1 = 0.58\, h_s$ (1.12)

At $x = x_1$, there will be no circulating eddy-current. But between $x = 0$ and x_1 the eddy-current will flow in one direction and between $x_1 = x_1$ and h_s, in the opposite direction (Figure 1.23d). Such current flow will result in distortion of the originally assumed flux distribution.

Neglecting the distortion of flux and noting that eddy-current in the lamina is due to (e_{edx} – e_{edav}), we have, the maximum value of eddy-current in the elemental lamina dx,

$$i_{edx} = \frac{1}{r_x} (e_{edx} - e_{edav})$$

where, r_x is the resistance of the elemental lamina per unit length = $\frac{\rho}{b_s dx}$

That is, $$i_{edx} = \frac{x f \mu_o b_s}{\rho w_s} i_m \left(\frac{h_s}{3} - \frac{x^2}{h_s} \right) dx \qquad (1.13)$$

A plot of i_{edx} against x is shown in Figure 1.22(d).

The eddy loss due to the above current is proportional to i^2_{edx}.

It is of interest to determine the eddy-loss as a fraction of the I^2 R-loss due to the current $i_m \cdot \frac{dx}{h_s}$ in the element. That is, (eddy loss/I^2R-Ioss) in the elemental lamina dx,

$$= \left(\frac{\pi f \mu_o b_s}{\rho w_s} \right)^2 h_s^2 \left(\frac{h_s}{3} - \frac{x^2}{h_s} \right)^2$$

$$= \alpha^4 h_3^2 \left(\frac{h_s}{3} - \frac{x^2}{h_s} \right)^2$$

Integrating the ratio over the conductor height h_s, we have, average $\frac{eddy \text{ loss}}{I^2R\text{ - loss}}$ in the conductor

$$= \frac{\alpha^4 h_s^2}{h_s} \int_0^{h_s} \left(\frac{h_s}{3} - \frac{x^2}{h_s} \right) dx$$

$$= \frac{4}{4.5} a^4 h_s^4 .$$

That is, the I^{2}R-loss due to the conductor current is augmented by a factor *kc* (generally called, eddy-loss factor or ratio), where,

$$k_c = \frac{\text{I}^2 R \; loss + eddy \text{ loss}}{I^2 R \text{ loss}}$$

$$= 1 + \frac{4}{4.5} (\alpha \; h_s)^4 \qquad (1.14)$$

At f = 50 Hz and at a temperature of 75°C,

for copper, $\alpha = 96 \; (b_s/w_s)^{1/2}$ (1.14a)

for aluminium, $\alpha = 75 \; (b_s/w_s)^{1/2}$ (114b)

Note :

(1) Equation (1.14) shows that the eddy-Joss is proportional to (conductor-depth)^4. Thus, the loss can be reduced by having reduced conductor depth.

(2) In cases where the design requirement is that the conductor-depth has to be large, sectionalised conductors (Figure 1.24a) are used with each section insulated from the other but connected in parallel. Eddy-current is confined to individual layer (Figure 1.24d) and production of excessive eddy-voltage is avoided (Figure 1.24c).

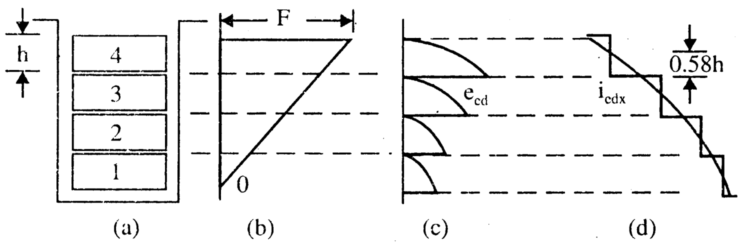


Figure 1.24 Eddy-currnet in sectionalised conductor in a slot.

Following the analysis as above, the eddy-loss ratio in the p-th layer is obtained approximately as,

$$k_{cp} = 1 + (ah_c)^4 \frac{p(p-1)}{3} \qquad (1.15)$$

The average loss ratio, considering all the m layers each of height h_c is,

$$k_{cav} = 1 + \frac{m^2}{9}(a\, h_c)^4 \tag{1.16}$$

(3) Equation (1.16) is valid so long the conductors are not connected in parallel. However in practice, parallel connection is essential so as to distribute the total current. But, since each layer occupies a different position in the slot, it is necessary to ensure complete balance between individual subdivisions, to keep circulating current to a minimum (art 1.7.2 (ii)). This is achieved by twisting or transposition (art. 7.3.1).)

Case II : Transformer Coils.

For transformers of normal design, eddy-current loss in conductors can be approximately obtained using equations (1.13) and (1.14) suitably, replacing b_s by H_{wdg}, ω_s by h_w, and h_s by c_1 (Figure 1.25).

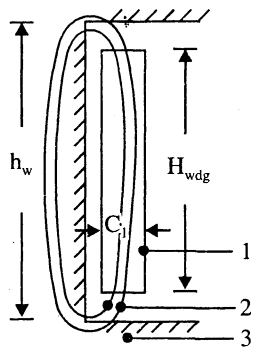


Figure 1.25 Eddy-current in transformer coils, 1–coil, 2–leakage flux, 3–yoke.

That is,

$$k_{cav} = 1 + \frac{4}{45}(a\, c_1)^4 \tag{1.17}$$

where,

$$a = 96\,(H_{wdg}/h_w)^{1/2} \text{ for copper} \tag{1.18a}$$

$$= 75\,(H_{wag}/h_w)^{1/2} \text{ for aluminium} \tag{1.18b}$$

Note : (1) As shown above, the eddy-loss is proportional to c_1^4. Subdivision of conductors into insulated sections with suitable transposition may be used to reduce the loss.

(2) In general, with suitable design, eddy-loss may be kept to a small value, about 5 percent of I^2R-loss at 75°C for small transformers and about 15 percent for larger units.

1.7.3 Magnetic Losses

Iron losses occur in the portions of magnetic circuit which are subjected to varying or alternating magnetic fields. The magnetic losses consist of,

(i) *Hysteresis loss :* For sinusoidally varying flux-density of peak value B_m, the specific loss,

$$W_h = K_h f B^n_m \text{ watt per kg.} \tag{1.19}$$

where, K_h is a proportionality constant which depends on the characteristics and volume of the magnetic material.

= 0.039 for medium and large transformers

= 0.063 for rotating machines;

and n, the exponent, ranging between 1.5 and 2.35.

[*Note :* Quite often, $n = 2$ is used for estimation of losses in electrical machinery.]

(ii) *Eddy-current loss :* For sinusoidally varying flux of peak density B_m, the specific eddy-current loss.

$$W_{ed} = K_{ed} B^2{}_m f^2 t^2 \text{ watt per kg.} \tag{1.20}$$

where, K_{ed} is another proportionality constant depending on the volume of the magnetic material and its resistivity,

= 0.0026 for medium and large transformers;

= 0.005 for core and 0.008 for teeth in rotating machines; and t is the thickness of lamination in metre.

The reduction of eddy-current loss by using laminations is a well-established method in transformers, a.c. rotating machines, and in the armature and pole-shoes of d.c. machines. The choice of lamination thickness is primarily dictated by eddy-current loss considerations as illustrated in Figures 1.26(a) and (b).

In a ferro-magnetic sheet subjected to a sinusoidal alternating flux, the permeability is not constant. For any particular thickness, the magnetic field strength reduces with the increase in permeability (Figure 1.26a). Figure 1.26(b) compares the degree of penetration of flux into HRS sheet with resistivity of 50 μ-ohm. cm. at 50 Hz of thicknesses 0.5 mm. and 2.0 mm., the

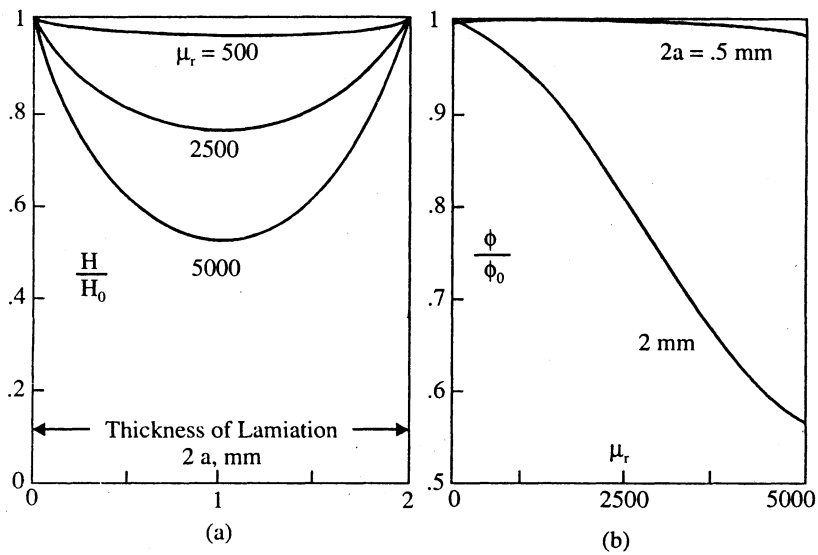


Figure 1.26 Choice of lamination thickness–(a) flux penetration for varying μ_r, (b) flux vs. μ_r. H_o–surface intensity, Φ_o–flux for uniform induction. H_1, Φ–respectively intensity and flux at any point inside.

ordinate representing the ratio of flux through the cross-section to the flux which would pass if the induction is uniform. It can be seen that for laminations of thickness upto 0.5 mm., the influence of permeability is negligible.

Note :

(1) The choice of lamination thickness on the lower side is guided by material handling consideration. Very thin laminations have low eddy-current loss but are difficult.to handle, and in rotating machines, teeth would bend too easily.

(2) The factor K_{ed} is inversely proportional to resistivity of the material and thus to limit the eddy loss, high resistivity material may be used.

(3) Preferred lamination thickness, as per ISS, are :–
non-oriented sheets : 0.35, 0.40, 0.45, 0.50, 0.63, 1.0 mm;
oriented sheet : 0.33 mm.

(iii) Apart from above, there are minor magnetic losses, such as, (a) stray losses, due to e.m.f. induced in adjacent conductors and metallic parts, e.g. end plates, end connectors, slot wedges, ventilating duct fingers, binding wires, etc.

(b) losses in teeth due to the non-sinusoidal field-form in the gap and losses due to tooth pulsation because of slot-opening.

These losses may cause high and inadmissible local temperature.

1.7.4 Supplementary Losses

(i) An insulating material subjected to an alternating field is the seat of losses distributed throughout its volume. The phenomenon can be depicted by a parallel combination of a capacitance C and a resistance R (Figure 1.27a), the latter giving rise to losses. If I_i be the total current through the dielectric and

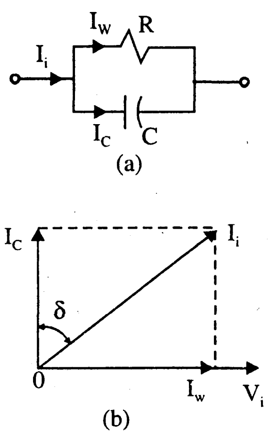


Figure 1.27 Pertaining dielectric loss.

V_i, the potential difference to which the insulation has been subjected to the dielectric loss

$$W_{di} = V_i \cdot I_w,$$

where, I_w is the loss component of current $I_i = \frac{V_i}{R}$

$= I_c \tan \delta$;

δ being the dielectric loss-angle = $\tan^{-1} \{I_w / I_c\}$.

That is, $$W_{di} = 2 \pi f v_i^2 C \tan \delta \qquad (1.21)$$

[*Note* : Dielectric losses in insulation distributed per unit, volume by conduction and periodic variation of the electric field are somewhat analogous to hysteresis loss in iron in a magnetic field. For most insulating materials such losses increase rapidly with temperature and voltage-gradient (voltage V_i / insulation thickness).]

(ii) *Losses at the brushes* (a) *Frictional* losses depend on contact surface area of the brushes with the commutator or slip-rings, the peripheral speed, and the brush-pressure. The following empirical equations may be used :–

For direct current machines

Brush-friction loss, $$W'_{bf} = \mu P_b V_c A_b \text{ watt} \qquad (1.22)$$

where, μ, the coefficient of friction depends somewhat on the nature of commutator surface, the peripheral speed V_c metre, sec^{-1} of commutator, and the material of the brush. Normally, μ ranges between 0.15 and 0.30.

P_b, the brush pressure, generally varies between 10,000 and 20,000 Newton, m^{-2}; A_b, the brush-contact surface, metre^2.

For machines with slip-rings

Brush-friction loss, $$W_{bf} = 3000 V_s A_b \text{ watt} \qquad (1.23)$$

V_s being the peripheral speed of slip-ring, metre, sec.$^{-1}$.

(b) Losses *due to voltage-drop at contact* depends on the quality of brushes, and is equal to the product of the voltage-drop at the brushes and the current in the brushes.

The voltage-drop can be taken as : 0.55 for metallographite, 1.4 for electro-graphite, 2.0 for hard and 2.5 for soft brushes.

(iii) Mechanical losses due to bearing friction depend approximately on the type of bearing, load on the bearing, and the peripheral speed of the bearing.

Ball bearings are generally used in small machines, and roller bearings in medium-power machines. The latter has a smaller coefficient of friction (μ), reduced axial length, and requires less maintenance.

With ball and roller bearings, bearing friction loss,

$$W_b = \mu P V_b / D_{dm} \text{ watt} \qquad (1.24)$$

where, P is the load on the bearing, Newton;

V_b, the peripheral speed of the bearing, metre, sec–;

and D_{dm}, the diameter of the circle through the centre of the ball for ball bearing; and diameter of the bearing for roller bearing; in metre.

μ may be taken as 1.5×10^{-6} for ball and 2.55×10^{-6} for roller bearing. With sleeve bearing,

$$W_b = 3000\ L_b\ V_b\ D_{dm}\ \text{watt} \tag{1.25}$$

where, L_b, metre, is the length of the bearing.

(iv) *Windage losses* due to air friction and ventilation depend on the type of ventilation, and is roughly proportional to the overall rotor surface area (= $\pi D\ L_A$, L_A being the overall axial length of the rotor including overhang; D, the diameter of the armature) and the peripheral speed.

For machines having rotor peripheral speed $V_r < 50$ metre, sec.$^{-1}$,

the windage loss, $$W_w = 0.08\ V_r^n\ L_A\ D\ \text{watt} \tag{1.26}$$

exponent n being equal to 2.0 for machines without fan, 2.5–3.0 for machines with fan.

For closed circuit ventilation schemes with air as the primary coolant (chapter 2), the windage loss can be determined from the following equations :-

$$W_w = (QHn_f)\ 10^{-2}\ \text{kw} \tag{1.27a}$$

where Q volume of air flowing through the machine required to give the prescribed temperature-rise

$$= 0.815 \frac{P_L}{\tau_a}\left(\frac{273 - t_{in}}{289}\right) \text{m}^3\ \text{sec}^{-1} \tag{1.27b}$$

P_L = losses to be dissipated, kW;
t_{in} = temperature of inlet air, °C;
τ_a = temperature-rise of air, °C.
H = pressure-drop across the machine and air cooler, kg. m-2:
η_f = fan efficiency.

1.8 TEMPERATURE-RISE

The losses in an electrical machine are converted into heat and cause the temperature of the machine to rise. Of the three materials viz. conducting, magnetic, and insulating used in electrical machines, the insulating material is the most vulnerable to temperature-rise, and it is often said that 'every 10°C rise in temperature in an electrical machine cuts the life of insulation by 50 percent'. Higher temperature gradually oxidise and carbonise the insulating materials and thereby restricts the output of the machine. Again, the limits of temperature-rise is closely linked with cooling, ventilation and enclosure of the machine.

1.8.1 Class of Duty

An analysis of various classes of duty as per IS will indicate that from the point of view of temperature-rise, the eight types of duty as classified in IS (Figure 1.28) can be broadly divided into two groups :–

(i) Continuous duty (Type S_1), in which the duration of operation of the machine under load is such that the machine reaches its thermal equilibrium (i.e. the maximum steady-state temperature-rise).

(ii) 'Non-continuous' duties (all types other than type S_1 i.e. type S_2 : Short-time duty; S_3 : Intermittent periodic duty; S_4 = Intermediate periodic duty with starting ; S_5 : Intermittent periodic duty with starting and braking; S_6 : Continuous duty with intermediate periodic loading; S_7 : Continuous duty with starting and braking; and type S_8 : Continuous duty with periodic speed changes) in which the duty cycle is shorter than the continuous duty, such that the machine never reaches its thermal equilibrium during the duty cycle.

From the user's point of view, choice of larger machine than what is required means operation at lower efficiency and unnecessary additional expenditure. Again, use of type motor (say, 10 kW) for duties other than continuous but of the same kW and class of insulation means lower maximum temperature-rise, and pessimistic use (though the life of the machine will be longer).

From the point of view of design, machines under the class of 'non-continuous' duty should be designed for higher curent-density (about 2 to 2.5 times for short-time duty upto 5 mins.) than that of continuous duty class (type S_1), since the machine can be allowed to attain the allowable maximum temperature-rise quicker than under continuous duty.

It is obvious that for maximum utilisation of material a designer should strive to attain the condition so that the maximum allowable temperature-rise is attained for the specific type of duty for which the machine is required.

1.8.2 Limits of Temperature-rise

It is a usual practice to indicate the allowable temperature-rise data on the name-plates of rotating machines. For example, the name-plate may show 50°C which means that the average temperature of the machine is 50°C above the ambient temperature.

[*Note* : (1) *Ambient temperature* means the temperature of the coolant at its inlet. This, for a large majority of rotating machines which are air-cooled, is the temperature of the surrounding air. For an oil-cooled transformer with cooling tubes or external radiator, the ambient temperature is the temperature of the oil at the bottom -end of the tubes or outlet end of the radiator respectively, through which cold oil enters the tank.

(2) With higher ambient temperature the capacity of the machine is reduced, since insulation used in the machine can withstand a maximum temperature depending on its class (Table 1.5), and thus with higher ambient temperature, the margin of safe temperature-rise to which the machine can be subjected to is reduced.

(3) The reference ambient temperatures as per IS are :-

(i) Transformer, with air as the coolant :
maximum ambient air temperature : 45°C;
maximum daily average ambient temperature :35°C;
maximum yearly weighted average ambient temperature :32°C;

(ii) Transformer, with water as the coolant : maximum ambient temperature : 30°C;

(iii) Rotating machines :

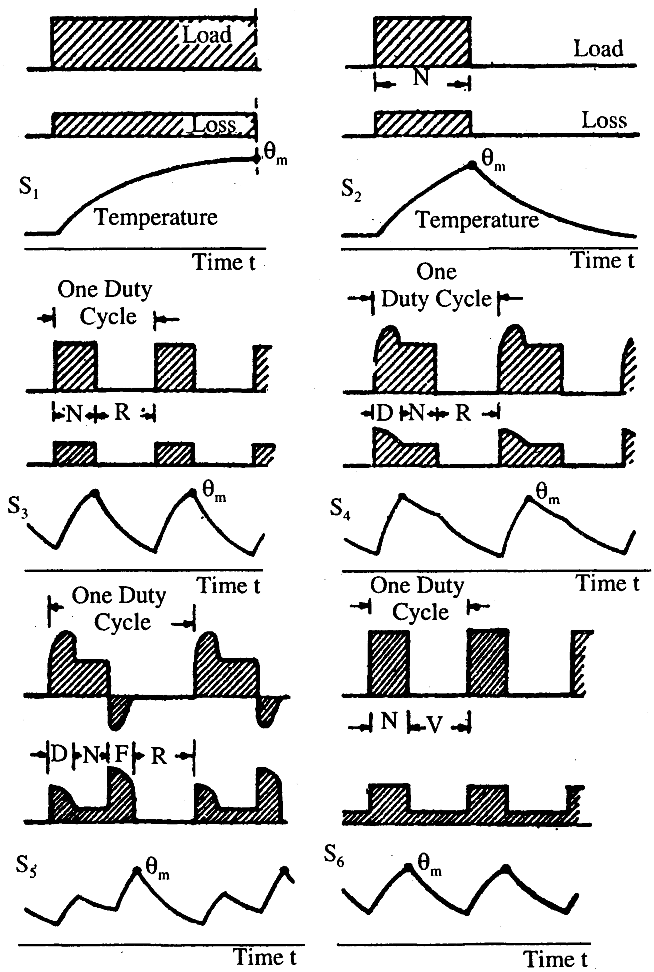


Figure 1.28 Classes of duty for rotating machines.
N–operation under rated load.
D–starting.
R–rest and de-energized,
F–electric braking,
V–operation on no-load.

For class of insulation A, E, B, F, H and altitude below 1000 metres : 40°C]

The limits of temperature-rise as adopted by the Indian Standard Institution are given in Table 1.6-for oil-immersed transformer, and Table 1.7–for rotating electrical machines. Three methods of determining the temperature-rise of windings and other parts are recognised :-

(1) Thermometer method (T H),
(2) Resistance method (R), and
(3) Embedded temperature-detector method (ETD).

[*Note :* (1) The tables concern machines suitable for operation at an altitude not exceeding 1000 metres above sea level. In case altitude exceeds, suitable adjustment of ambient temperature and temperature-rise is to be made as specified in relevant IS.

Table 1.6 Limits of Temperature-rise for Oil-immersed Transformers,

	Method of measurement	Cooling classification	Temperature-rise. °C
1. Winding	TH	ON, OB, OW	55
		OFN, OFB	60
		OFW	65
2. Oil	TH in top oil	All	45

Table 1.7 Limits of Temperature-rise for Rotating Electrical Machanies.

Part	Method of measurement	Class of insulation A	E	B	F	H
A. C. Winding						
1. Air-cooled						
(a) Output 5 MW or more, or, core-length 1 m or more	R, ETD	60	70	80	100	125
(b) Of machines smaller	TH	50	65	70	85	105
than in (a)	R	60	75	80	100	125
2. Indirect Hydrogen-cooled : Absolute hydrogen-pressure						
20.28×10^4 to 28.84×10^4				80	100	
29.74×10^4				75	95	
39.35×10^4	ETD			70	90	
49.36×10^4				65	85	
59.16×10^4				62	82	
Commutator Winding	TH	50	65	70	85	105
	R	60	75	80	100	125
D. C. Fied Winding						
1. Low resistance, single layer;						125
and compensating winding.	TH,R	60	75	80	100	
2. Single layer winding with						513
exposed bare surface	TH,R	65	80	90	110	
3. Of a.c. and d.c. machines other	TH	50	65	70	85	105
than (1) and (2) above	R	60	75	80	100	125
Other Parts						
1. Permanently short-circuited insulated winding ; Magnetic cores and other parts in contact with windings	TH	60	75	80	100	125
2. Commutator and slip rings	TH	60	70	80	90	100

2. For rotating electrical machines,
   (a) with class Y, the limits of permissible temperature-rise are 15°C lower than those with class A.
   (b) Suitable adjustment of the limits of temperature-rise of stator winding is to be made as per IS, for rated voltage in excess of 11 kv.
   (c) When the machine is designed to operate with a cooling medium temperature other than 40°C, suitable adjustment of the permissible temperature-rise shall be made as specified in relevant IS.]

SHORT QUESTIONS

1.1 Mention 4 goals which a designer should strive to reach.

1.2 Write a typical flow-chart for the design of electrical machines.

1.3 Compare 'total computerisation' of design with 'partial computerisation'.

1.4 Mention 2 points in favour of standardisation.

1.5 'To the designer, standardisation means rigidity'-explain.

1.6 Mention important specifications of (i) transformer, (ii) d.c. machine, (iii) induction motor.

1.7 What is the function of steel core in electrical machines ?

1.8 What are the important design and constructional elements of a transformer ?

1.9 Why is the 5-limb pattern commonly adopted for a large three phase transformer ?

1.10 What are the functions of a conservator ?

1.11 Mention 2 purposes which oil serves in an oil-immersed transformer.

1.12 State important constructional elements of a rotating electrical machine.

1.13 Why are turbo-generators of non-salient pole type, and water-wheel generators of salient-pole type ?

1.14 Compare copper and aluminium as conducting materials for electrical machines.

1.15 Show that, for the same i^2r-losses, a general purpose standard electrical machine wound with aluminium has a power rating of approximately 78% of that wound with copper.

1.16 What is Superconductivity ? Name 3 important superconducting compounds.

1.17 Indicate the feasibility of using superconductor in large (i) transformers, (ii) turbogenerators.

1.18 State 5 points in favour of adding silicon (about 3%) to iron in electric steel.

1.19 Compare HRS and CROS.

1.20 Write a note on the use of CROS in (i) transformers, (ii) rotating machines.

1.21 State 2 advantages and 2 disadvantage in using strip-wound transformer core with CROS.

1.22 What is Mitre ?

1.23 Mention 3 fundamental requirements for a good insulating material.

1.24 What is varnish impregnation ?

1.25 Enumerate the component losses in a (i) transformer, (ii) rotating machine.

1.26 Compute the i^2r-loss in a coil when it carries (i) a direct current and a superposed sinusoidal alternating current; (a) a non-sinusoidal alternating current.

1.27 What is the necessity of using sectionalised conductors in large machines ?

1.28 Why is transposition or twisting of conductors used ?

1.29 Mention 8 classes of duty for electrical machines.

1.30 Name 3 recognised methods of determining temperature rise of windings and other parts in electrical machines.

1.31 State 'true' or 'false' :-

(i) In large transformers, capacitive protection rings and electro-static shieldings are provided for protection against voltage surges.

(ii) Laminations must be assembled tight to reduce eddy-current losses.

(iii) Tight lamination assembly reduces vibration and noise.

(iv) In turbogenerators, large centrifugal forces necessitate the use of rotor cores assembled from thin steel plates.

(v) Cold-rolled sheets as compared to hot-rolled has larger magnetic field intensity at a working flux-density.

(vi) Studies have shown that superconductors are not economical for large transformers.

(vii) Hot rolling results in lesser variation in thickness of sheets as compared with cold rolling.

(viii) Class E insulation has a higher limiting working temperature as compared with class B.

(ix) Eddy-current loss in a conductor is reduced with increased conductor depth in the slot of a rotating machine.

(x) The magnetic field strength in a ferro-magnetic sheet of a particular thickness subjected to sinusoidal flux increases with the increase in permeability.

(xi) Machines with non-continuous duty should be designed with larger current density.

(xii) With higher ambient temperature, the capacity of a machine for the same class of insulation, is increased.