INTRODUCTION

Major considerations in Electrical Machine Design - Electrical Engineering Materials – Space factor – Choice of Specific Electrical and Magnetic loadings - Thermal considerations - Heat flow – Temperature rise - Rating of machines – Standard specifications.

1.1. Major considerations in Electrical Machine Design

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

Magnetic circuit or the flux path:

Should establish required amount of flux using minimum MMF. The core losses should be less.

Electric circuit or windings:

Should ensure required EMF is induced with no complexity in winding arrangement. The copper losses should be less.

Insulation:

Should ensure trouble free separation of machine parts operating at different potential and confine the current in the prescribed paths.

Cooling system or ventilation:

Should ensure that the machine operates at the specified temperature.

Machine parts:

Should be robust.

The art of successful design lies not only in resolving the conflict for space between iron, copper, insulation and coolant but also in optimization of cost of manufacturing, and operating and maintenance charges.

The factors, apart from the above, that requires consideration are

a. Limitation in design (saturation, current density, insulation, temperature rise etc.,)

b. Customer’s needs

c. National and international standards

d. Convenience in production line and transportation e. Maintenance and repairs

f. Environmental conditions etc.

Limitations in design: The materials used for the machine and others such as cooling etc., imposes a limitation in design. The limitations stem from saturation of iron, current density in conductors, temperature, insulation, mechanical properties, efficiency, power factor etc.

a. Saturation: Higher flux density reduces the volume of iron but drives the iron to operate beyond knee of the magnetization curve or in the region of saturation. Saturation of iron poses a limitation on account of increased core loss and excessive excitation required to establish a desired value of flux. It also introduces harmonics.

b. Current density: Higher current density reduces the volume of copper but increases the losses and temperature.

c. Temperature: poses a limitation on account of possible damage to insulation and other materials.

d. Insulation (which is both mechanically and electrically weak): poses a limitation on account of breakdown by excessive voltage gradient, mechanical forces or heat.

e. Mechanical strength of the materials poses a limitation particularly in case of large and high speed machines.

f. High efficiency and high power factor poses a limitation on account of higher capital cost. (A low value of efficiency and power factor on the other hand results in a high maintenance cost).

g. Mechanical Commutation in dc motors or generators leads to poor commutation.

Apart from the above factors Consumer, manufacturer or standard specifications may pose a limitation.

1.2. Materials for Electrical Machines

The main material characteristics of relevance to electrical machines are those associated with conductors for electric circuit, the insulation system necessary to isolate the circuits, and with the specialized steels and permanent magnets used for the magnetic circuit.

Conducting materials

Commonly used conducting materials are copper and aluminum. Some of the desirable properties a good conductor should possess are listed below.

1. Low value of resistivity or high conductivity
2. Low value of temperature coefficient of resistance
3. High tensile strength
4. High melting point
5. High resistance to corrosion

6. Allow brazing, soldering or welding so that the joints are reliable
7. Highly malleable and ductile
8. Durable and cheap by cost

Some of the properties of copper and aluminum are shown in the table

Sl. No	**Particulars**	**Copper**	**Aluminum**
1	Resistivity at 20^0C	0.0172 ohm / m/ mm^2	0.0269 ohm / m/ mm^2
2	Conductivity at 20^0C	58.14 x 10^6S/m	37.2 x 10^6S/m
3	Density at 20^0C	8933kg/m^3	2689.9m^3
4	Temperature coefficient (0-100^oC)	0.393 % per ^{0}C	0.4 % per ^{0}C
		Explanation: If the temperature increases by 1^oC, the resistance increases by 0.4% in case of aluminum	
5	Coefficient of linear expansion (0-100^oC)	16.8x10^{-6} per ^{o}C	23.5 x10^{-6} per ^{o}C
6	Tensile strength	25 to 40 kg / mm^2	10 to 18 kg / mm^2
7	Mechanical property	highly malleable and ductile	not highly malleable and ductile
8	Melting point	1083^0C	660^0C
9	Thermal conductivity (0-100^oC)	599 W/m ^{0}C	238 W/m ^{0}C
10	Jointing	can be easily soldered	cannot be soldered easily

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

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

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

1. Low reluctance or should be highly permeable or should have a high value of relative permeability μr.
2. High saturation induction (to minimize weight and volume of iron parts)
3. High electrical resistivity so that the eddy EMF and the hence eddy current loss is less
4. Narrow hysteresis loop or low Coercivity so that hysteresis loss is less and efficiency of operation is high
5. A high curie point. (Above Curie point or temperature the material loses the magnetic property or becomes paramagnetic, that is effectively non-magnetic)
6. Should have a high value of energy product (expressed in joules / m3).

Magnetic materials can broadly be classified as Diamagnetic, Paramagnetic, Ferromagnetic, Antiferromagnetic and Ferrimagnetic materials. Only ferromagnetic materials have properties that are well suitable for electrical machines. Ferromagnetic properties are confined almost entirely to iron, nickel and cobalt and their alloys. The only exceptions are some alloys of manganese and some of the rare earth elements.

The relative permeability μr of ferromagnetic material is far greater than 1.0. When ferromagnetic materials are subjected to the magnetic field, the dipoles align themselves in the direction of the applied field and get strongly magnetized.

Further the Ferromagnetic materials can be classified as Hard or Permanent Magnetic materials and Soft Magnetic materials.

a) Hard or permanent magnetic materials have large size hysteresis loop (obviously hysteresis loss is more) and gradually rising magnetization curve.

Ex: carbon steel, tungsten steal, cobalt steel, alnico, hard ferrite etc.

b) Soft magnetic materials have small size hysteresis loop and a steep magnetization curve.

Ex: i) cast iron, cast steel, rolled steel, forged steel etc., (in the solid form).

Generally used for yokes poles of dc machines, rotors of turbo alternator etc., where steady or dc flux is involved.

ii) Silicon steel (Iron + 0.3 to 4.5% silicon) in the laminated form. Addition of silicon in proper percentage eliminates ageing & reduce core loss. Low silicon content steel or dynamo grade steel is used in rotating electrical machines and are operated at high flux density. High content silicon steel (4 to 5% silicon) or transformer grade steel (or high resistance steel) is used in transformers. Further sheet steel may be hot or cold rolled. Cold rolled grain oriented steel (CRGOS) is costlier and superior to hot rolled. CRGO steel is generally used in transformers.

c) Special purpose Alloys:

Nickel iron alloys have high permeability and addition of molybdenum or chromium leads to improved magnetic material. Nickel with iron in different proportion leads to

(i) High nickel permalloy (iron +molybdenum +copper or chromium), used in current transformers, magnetic amplifiers etc.,

(ii) Low nickel Permalloy (iron +silicon +chromium or manganese), used in transformers, induction coils, chokes etc.

(iii) Perminvor (iron +nickel +cobalt)

(iv) Pemendur (iron +cobalt +vanadium), used for microphones, oscilloscopes, etc. (v) Mumetal (Copper + iron)

d) Amorphous alloys (often called metallic glasses):

Amorphous alloys are produced by rapid solidification of the alloy at cooling rates of about a million degrees centigrade per second. The alloys solidify with a glass-like atomic structure which is non-crystalline frozen liquid. The rapid cooling is achieved by causing the molten alloy to flow through an orifice onto a rapidly rotating water cooled drum. This can produce sheets as thin as 10μm and a meter or more wide.

These alloys can be classified as iron rich based group and cobalt based group.

Insulating materials.

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

1) Should have high dielectric strength.

2) Should with stand high temperature.

3) Should have good thermal conductivity

4) Should not undergo thermal oxidation

5) Should not deteriorate due to higher temperature and repeated heat cycle

6) Should have high value of resistivity (like 1018 Ωcm)

7) Should not consume any power or should have a low dielectric loss angle δ

8) Should withstand stresses due to centrifugal forces (as in rotating machines), electro dynamic or mechanical forces (as in transformers)

9) Should withstand vibration, abrasion, bending

10) Should not absorb moisture

11) Should be flexible and cheap

12) Liquid insulators should not evaporate or volatilize

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

Solid: Used with field, armature, and transformer windings etc. The examples are:

1) Fibrous or inorganic animal or plant origin, natural or synthetic paper, wood, card board, cotton, jute, silk etc.,

2) Plastic or resins. Natural resins-lac, amber, shellac etc.,

Synthetic resins-phenol formaldehyde, melamine, polyesters, epoxy, silicon resins, bakelite, Teflon, PVC etc

3) Rubber : natural rubber, synthetic rubber-butadiene, silicone rubber, hypalon, etc.,

4) Mineral : mica, marble, slate, talc chloride etc.,

5) Ceramic : porcelain, steatite, alumina etc.,

6) Glass : soda lime glass, silica glass, lead glass, borosilicate glass

7) Non-resinous : mineral waxes, asphalt, bitumen, chlorinated naphthalene, enamel etc.,

Liquid: Used in transformers, circuit breakers, reactors, rheostats, cables, capacitors etc., & for impregnation. The examples are:

1) Mineral oil (petroleum by product)

2) Synthetic oil askarels, pyranols etc.,

3) Varnish, French polish, lacquer epoxy resin etc.,

Gaseous: The examples are:

1) Air used in switches, air condensers, transmission and distribution lines etc.,

2) Nitrogen use in capacitors, HV gas pressure cables etc.,

3) Hydrogen though not used as a dielectric, generally used as a coolant

4) Inert gases neon, argon, mercury and sodium vapors generally used for neon sign lamps.

5) Halogens like fluorine, used under high pressure in cables

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

1.3. Space factor:

Window space factor Kw

Window space factor is defined as the ratio of copper area in the window to the area of the window.

For a given window area, as the voltage rating of the transformer increases, quantity of insulation in the window increases, area of copper reduces. Thus the window space factor reduces as the voltage increases.

1.4. Choice of Specific Electrical and Magnetic loadings

Specific magnetic loading:

Following are the factors which influences the performance of the machine.

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

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

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

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

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

Specific Electric Loading:

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

(i) Copper loss: Higher the value of q larger will be the number of armature of conductors which results in higher copper loss. This will result in higher temperature rise and reduction in efficiency.

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

(iii) Synchronous reactance: High value of q leads to higher value of leakage reactance and armature reaction and hence higher value of synchronous reactance. Such machines will have poor voltage regulation, lower value of current under short circuit condition and low value of steady state stability limit and small value of synchronizing power.

(iv) Stray load losses: With increase of q stray load losses will increase. Values of specific magnetic and specific electric loading can be selected from Design Data Hand Book for salient and non salient pole machines.

Separation of D and L: Inner diameter and gross length of the stator can be calculated from D^2L product obtained from the output equation. To separate suitable relations are assumed between D and L depending upon the type of the generator. Salient pole machines: In case of salient pole machines either round or rectangular pole construction is employed. In these types of machines the diameter of the machine will be quite larger than the axial length.

1.5. Heat flow

The heat is removed by convection, conduction and radiation. Usually, the convection through air, liquid or steam is the most significant method of heat transfer. Forced convection is, inevitably, the most efficient cooling method if we do not take direct water cooling into account. The cooling design for forced convective cooling is also straightforward: the designer has to ensure that a large enough amount of coolant flows through the machine. This means that the cooling channels have to be large enough. If a machine with open-circuit cooling is of IP class higher than IP 20, using heat exchangers to cool the coolant may close the coolant flow.

If the motor is flange mounted, a notable amount of heat can be transferred through the flange of the machine to the device operated by the motor. The proportion of heat transfer by radiation is usually moderate, yet not completely insignificant. A black surface of the machine in particular promotes heat transfer by radiation.

Conduction

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

1.6. Temperature rise

The temperature rise of a machine depends on the power loss per cooling area S

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

The most important factor in thermal design is, however, the temperature of ambient fluid, as it determines the maximum temperature rise with the heat tolerance of the insulation. Second, in addition to the question of heat removal, the distribution of heat in different parts of the machine also has to be considered. This is a problem of heat diffusion, which is a complicated three-dimensional problem involving numerous elements such as the question of heat transfer from the conductors over the insulation to the stator frame. It should be borne in mind that the various empirical equations are to be employed with caution. The distribution of heat in the machine can be calculated when the distribution of losses in different parts of the machine and the heat removal power are exactly known. In transients, the heat is distributed completely differently than in the stationary state. For instance, it is possible to overload the motor considerably for a short period of time by storing the excess heat in the heat capacity of the machine

1.7. Rating of machines

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

The rating of machine refer to the whole of the numerical values of electrical and mechanical quantities with their duration and sequence assigned to the machines by the manufacturer and stated on the rating plate, the machine complying with the specified conditions.

Standard specifications.

1. Output : kW (for generators), kW or Hp (for motors)
2. Voltage : V volt
3. Speed : N rpm
4. Rating : Continuous or Short time
5. Temperature rise: θ^0C for an ambient temperature of 40^0C
6. Cooling : Natural or forced cooling
7. Type: Generator or motor, separately excited or self-excited-shunt, series, or compound, if compound type of connection – long or short shunt, type of compounding – cumulative or differential, degree of compounding – over, under or level. With or without inter poles, with or without compensating windings,with or without equalizer rings in case of lap winding.
8. Voltage regulation (in case of generators) : Range and method
9. Speed control (in case of motors) : range and method of control
10. Efficiency: must be as for as possible high (As the efficiency increases, cost of the machine also increases).
11. Type of enclosure: based on the field of application – totally enclosed, screen protected, drip proof, flame proof, etc.,
12. Size of the machine etc.,