
Electrical Machine Design

Fundamental aspects of electrical machine design

Introduction

The magnetic flux in all electrical machines (generators, motors and transformers) plays an important role in converting or transferring the energy. Field or magnetizing winding of rotating machines produces the flux while armature winding supplies either electrical power or mechanical power. In case of transformers primary winding supplies the power demand of the secondary.

The basic design of an electrical machine involves the dimensioning of the magnetic circuit, electrical circuit, insulation system etc., and is carried out by applying analytical equations.

A designer is generally confronted with a number of problems for which there may not be one solution, but many solutions. A design should ensure that the products perform in accordance with the requirements at higher efficiency, lower weight of material for the desired output, lower temperature rise and lower cost. Also they are to be reliable and durable.

A practical designer must effect the design so that the stock (standard frames, punching etc.) is adaptable to the requirements of the specification. The designer must also effect some sort of compromise between the ideal design and a design which comply with manufacturing conditions. A electrical designer must be familiar with the,

a. National and international standards

Indian Standard (IS), Bureau of Indian Standard (BIS),

India British Standard (BS), England

International Electrotechnical Commission (IEC)

NEMA (The National Electrical Manufacturers Association).

b. Specifications (that deals with machine ratings, performance requirements etc., of the consumer)

c. Cost of material and labour

d. Manufacturing constraints etc.

A designer can refer to Design Data Handbook which is a source of design procedure, properties of materials, ranges of design parameters etc., and manufacturer's brochure.

As the design involves a number of assumptions and constraints, final design values can be obtained only by iterative methods. Computer plays a vital role in arriving at the final values. By Finite Element Method (FEM), the effect of a single parameter on the dynamical performance of the machine can be studied. Furthermore, some tests, which are not even feasible in laboratory setup, can be virtually performed by Finite Element Method.

The design problems, that have been considered to solve in the latter chapters, are of different nature from the design worked out in detail in respect of any machine.

Factors for consideration 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,

1. **Magnetic circuit or the flux path:** Should establish required amount of flux using minimum mmf. The core losses should be less.
2. **Electric circuit or windings:** Should ensure required emf is induced with no complexity in winding arrangement. The copper losses should be less.
3. **Insulation:** Should ensure trouble free separation of machine parts operating at different potential and confine the current in the prescribed paths.
4. **Cooling system or ventilation:** Should ensure that the machine operates at the specified temperature.
5. **Machine parts:** Should be robust.

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

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

- a. Limitation in design (saturation, current density, insulation, temperature rise etc.)
- b. Customer's needs
- c. National and international standards
- d. Convenience in production line and transportation
- e. Maintenance and repairs
- f. Environmental conditions etc.

Limitations in design

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

- a. **Saturation:** Higher flux density reduces the volume of iron but drives the iron to operate beyond knee of the magnetization curve or in the region of saturation. Saturation of iron poses a limitation on account of increased core loss and excessive excitation required to establish a desired value of flux. It also introduces harmonics.
- b. **Current density:** Higher current density reduces the volume of copper but increases the losses and temperature.
- c. **Temperature:** poses a limitation on account of possible damage to insulation and other materials.
- d. **Insulation** (which is both mechanically and electrically weak): poses a limitation on account of breakdown by excessive voltage gradient, mechanical forces or heat.

- e. Mechanical strength of the materials poses a limitation particularly in case of large and high speed machines.
- f. High efficiency and high power factor poses a limitation on account of higher capital cost. (A low value of efficiency and power factor on the other hand results in a high maintenance cost).
- g. Mechanical Commutation in dc motors or generators leads to poor commutation.

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

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-2.

Table-2

Sl. No	Particulars	Copper	Aluminum
1	Resistivity at 20 ⁰ C	0.0172 ohm / m/ mm ²	0.0269 ohm / m/ mm ²
2	Conductivity at 20 ⁰ C	58.14 x 10 ⁶ S/m	37.2 x 10 ⁶ S/m
3	Density at 20 ⁰ C	8933kg/m ³	2689.9m ³
4	Temperature coefficient (0-100 ⁰ C)	0.393 % per ⁰ C	0.4 % per ⁰ C
Explanation: If the temperature increases by 1 ⁰ C, the resistance increases by 0.4% in case of aluminum			
5	Coefficient of linear expansion (0-100 ⁰ C)	16.8x10 ⁻⁶ per ⁰ C	23.5 x10 ⁻⁶ per ⁰ 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 ⁰ C	660 ⁰ C
9	Thermal conductivity (0-100 ⁰ C)	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 days 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 μ_r .
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 μ_r 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 steel, 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 10 μ m and a metre or more wide.

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

Material	Maximum permeability $\mu \times 10^{-3}$	Saturation magnetization in tesla	Coercivity A/m	Curie temperature $^{\circ}$ C	Resistivity $m \times 10^8$
3% Si grain oriented	90	2.0	6-7	745	48
2.5% Si grain non -oriented	8	2.0	40	745	44
<0.5% Si grain non oriented	8	2.1	50-100	770	12
Low carbon iron	3-10	2.1	50-120	770	12
78% Ni and iron	250-400	0.8	1.0	350	40
50% Ni and iron	100	1.5-1.6	10	530	60
Iron based Amorphous	35-600	1.3-1.8	1.0-1.6	310-415	120-140

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 $10^{18} \Omega\text{cm}$)
- 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 insulating material is sometimes used in a broader sense to designate also insulating liquids, gas and vacuum.

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

- 1) Fibrous or inorganic animal or plant origin, natural or synthetic paper, wood, card board, cotton, jute, silk etc., rayon, nylon, terelane, asbestos, fiber glass 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.

Classification of insulating materials based on thermal consideration

The insulation system (also called insulation class) for wires used in generators, motors transformers and other wire-wound electrical components is divided into different classes according to the temperature that they can safely withstand.

As per Indian Standard (Thermal evaluation and classification of Electrical Insulation, IS.No.1271,1985, first revision) and other international standard insulation is classified by letter grades A,E,B,F,H (previous Y,A,E,B,F,H,C).

Insulation class		Maximum operating temperature in °C	Typical materials
Previous	Present		
Y		90	Cotton, silk, paper, wood, cellulose, fiber etc., without impregnation or oil immersed
A	A	105	The material of class Y impregnated with natural resins, cellulose esters, insulating oils etc., and also laminated wood, varnished paper etc.
E	E	120	Synthetic resin enamels of vinyl acetate or nylon tapes, cotton and paper laminates with formaldehyde bonding etc.,
B	B	130	Mica, glass fiber, asbestos etc., with suitable bonding substances, built up mica, glass fiber and asbestos laminates.
F	F	155	The materials of Class B with more thermal resistance bonding materials
H	H	180	Glass fiber and asbestos materials and built up mica with appropriate silicone resins
C	C	>180	Mica, ceramics, glass, quartz and asbestos with binders or resins of super thermal stability.

The maximum operating temperature is the temperature the insulation can reach during operation and is the sum of standardized ambient temperature i.e. 40 degree centigrade, permissible temperature rise and allowance tolerance for hot spot in winding. For example, the maximum temperature of class B insulation is (ambient temperature 40 + allowable temperature rise 80 + hot spot tolerance 10) = 130°C.

Insulation is the weakest element against heat and is a critical factor in deciding the life of electrical equipment. The maximum operating temperatures prescribed for different class of insulation are for a healthy lifetime of 20,000 hours. The height temperature permitted for the machine parts is usually about 200°C at the maximum. Exceeding the maximum operating temperature will affect the life of the insulation. As a rule of thumb, the lifetime of the winding insulation will be reduced by half for every 10 °C rise in temperature. The present day trend is to design the machine using class F insulation for class B temperature rise.