

1.1. Basic concepts of design

- Purpose of a design is to determine dimensions of machine parts, material specification, detailed drawings and manufacturing.
- Design is carried out by keeping in mind to optimize cost, volume and weight to achieve desired performance as per specification.
- Designer needs to be familiar with international/national standards, properties of electrical materials, mechanical and metallurgical properties of steel, electrical laws, heat transfer laws, prices of materials, foreign exchange rates, types of duties levied on products and labor rates.
- Design involves a number of assumptions and constraints, hence final design values can be obtained by iterative methods or using software.
- The art of good design is not only to resolve conflict of space between iron, copper, insulation and coolant but also to optimize manufacturing, operating and maintenance cost.
- Several design standards such as Indian Standard (IS), Bureau of Indian Standard (BIS), British Standard (BS), International Electrotechnical Commission (IEC), NEMA (The National Electrical Manufacturers Association) are widely followed by manufacturers for electrical machine design.

1.2. Output equation of rotating machines

(a) DC machines

- Output equation of a rotating machine is the mathematical expression that relates the main dimension, specific magnetic loading, specific electric loading and speed.

P_a = Power developed by armature (kW)

P = Rating of machine (kW)

E = Generated emf (V)

I_a = Armature current (A)

I_z = Current in each conductor (A)

n_s = Synchronous speed (rps)

n = Machine speed (rps)

p = Number of pole

a = Number of parallel path

Z = Total number of armature conductor

ϕ = Total flux around the airgap (Wb)

B_{av} = Specific magnetic loading (Wb/m²)

ac = Specific electric loading (AT/m)

D = Armature diameter (m)

L = Armature core length (m)

C_o = Output co-efficient

- Power developed by armature in kW

$$\begin{aligned}
 P_a &= \text{Generated emf} \times \text{Armature current} \times 10^{-3} \\
 &= E \times I_a \times 10^{-3} \\
 &= \frac{\phi Z n p}{a} \times I_a \times 10^{-3} \\
 &= (\phi p) \left(\frac{I_a Z}{a} \right) \times n \times 10^{-3} \\
 &= (\phi p) (I_z Z) \times n \times 10^{-3} \\
 &= (\text{Total magnetic loading}) (\text{Total electric loading}) \times n \times 10^{-3} \\
 &= (\pi D L B_{av}) (\pi D a c) \times n \times 10^{-3} \\
 &= (\pi^2 B_{av} a c \times 10^{-3}) D^2 L n \\
 &= C_o D^2 L n
 \end{aligned}$$

(b) AC machines

Q = Output (kVA)

m = Number of phases

E_{ph} = Voltage per phase (V)

I_{ph} = Current per phase (A)

T_{ph} = Turns per phase

K_w = Constant

p = Number of pole

Z = Total number of armature conductor

ϕ = Total flux around the airgap (Wb)

B_{av} = Specific magnetic loading (Wb/m²)

ac = Specific electric loading (AT/m)

C_o = Output co-efficient

- Output of a machine

$$\begin{aligned}
 Q &= \text{Number of phases} \times \text{Voltage per phase} \times \text{Current per phase} \times 10^{-3} \\
 &= m \times E_{ph} \times I_{ph} \times 10^{-3} \\
 &= m \times (4.44 f \phi T_{ph} K_w) \times I_{ph} \times 10^{-3} \\
 &= m \times \left(4.44 \left(\frac{p n_s}{2} \right) \phi \left(\frac{Z}{2m} \right) K_w \right) \times I_z \times 10^{-3} \\
 &= 1.11 K_w (\phi p) (I_z Z) \times n_s \times 10^{-3} \\
 &= 1.11 K_w (\text{Total magnetic loading}) (\text{Total electric loading}) \times n_s \times 10^{-3} \\
 &= 1.11 K_w (\pi D L B_{av}) (\pi D a c) \times n_s \times 10^{-3} \\
 &= (1.11 \pi^2 B_{av} a c K_w \times 10^{-3}) D^2 L n_s \\
 &= C_o D^2 L n_s
 \end{aligned}$$

1.3. Output equation of 3-phase transformer

- Output equation of transformer is the mathematical expression relating kVA rating with main dimension. In 3-phase transformer one window contains half of high voltage (HV) winding and half of low voltage (LV) winding of two consecutive phase. Two such windows forms entire assembly.

Let,

Q = Output of transformer (kVA)

f = Supply frequency (Hz)

ϕ_m = Maximum flux (Wb)

B_m = Maximum flux density (Wb/m²)

δ = Current density (A/mm²)

A_i = Net cross section area of core (m²)

A_c = Total copper area in window (m²)

A_w = Total area of window (m²)

K_w = Window space factor

T_{HV} = Number of high voltage winding turns

T_{LV} = Number of low voltage winding turns

I_{HV} = Phase current in high voltage winding (A)

I_{LV} = Phase current in low voltage winding (A)

a_{HV} = Cross section area of high voltage winding conductor (mm²)

a_{LV} = Cross section area of low voltage winding conductor (mm²)

V_{HV} = Phase voltage of high voltage winding (V)

V_{LV} = Phase voltage of low voltage winding (V)

E_{HV} = Phase induced emf in high voltage winding (V)

E_{LV} = Phase induced emf in low voltage winding (V)

E_{LV} = Phase induced emf in low voltage winding (V)

$$\begin{aligned}
 A_c &= 2 \left[(T_{HV} \times a_{HV}) + (T_{LV} \times a_{LV}) \right] \\
 &= 2 \left[\left(T_{HV} \times \left(\frac{I_{HV}}{\delta} \right) \right) + \left(T_{LV} \times \left(\frac{I_{LV}}{\delta} \right) \right) \right] \\
 &= \frac{2}{\delta} \left[(T_{HV} \times I_{HV}) + (T_{LV} \times I_{LV}) \right] \\
 &= \frac{2}{\delta} \left[(\text{mmf of HV winding}) + (\text{mmf of LV winding}) \right] \\
 &= \frac{2}{\delta} \left[(AT) + (AT) \right] \\
 A_c &= \frac{4}{\delta} [AT]
 \end{aligned}$$

Also, window space factor can be defined as

$$K_w = \frac{\text{Total copper area in window}}{\text{Total area of window}}$$

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

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

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

Rating of 3-phase transformer in kVA

$$Q = 3 \times V_{HV} \times I_{HV} \times 10^{-3}$$

$$\cong 3 \times E_{HV} \times I_{HV} \times 10^{-3}$$

$$= 3 \times (4.44 \times f \times \phi_m \times T_{HV}) \times I_{HV} \times 10^{-3}$$

$$= 3 \times (4.44 \times f \times \phi_m) \times (I_{HV} \times T_{HV}) \times 10^{-3}$$

$$= 3 \times (4.44 \times f \times \phi_m) \times \left(\frac{K_w A_w \delta}{4} \right) \times 10^{-3} \quad \left(\because AT = \frac{K_w A_w \delta}{4} \right)$$

$$= 3 \times (1.11 \times f \times (B_m \times A_i)) \times (K_w A_w \delta) \times 10^{-3}$$

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

1.4. Factors affecting size of rotating machines

- Output equation of machine reflects that the product D^2L will decrease with the increase of speed and/or output coefficient.

$$D^2L = \frac{P_a}{C_o n}$$

- Product D^2L reflects the volume of active parts of rotating machine, hence decrease in its value ultimately reduces the size and cost.

(a) Speed

- Volume of active part of rotating machine varies inversely proportional to the speed.
- For the same output a machine designed with greater speed will have smaller size and hence lesser cost. When the speed is not specific criteria, highest practical speed should be selected.

(b) Output coefficient

$$C_o = \frac{P_a}{D^2 L n} = \pi^2 B_{av} a c \times 10^{-3}$$

- Volume of active part of rotating machine varies inversely proportional to the output coefficient.
- Economic point of view, output coefficient should be high as possible to reduce size and cost.
- As output coefficient is product of specific magnetic loading and specific electrical loading, its value depends on selection of these loadings.
- Higher value of specific magnetic loading and electrical loading gives much higher value of output coefficient which further helps to reduce volume of machine and consecutively size and cost.
- But beyond some extent higher value of specific magnetic loading and electrical loading adversely affect the performance characteristics such as temperature rise, efficiency, power factor, commutation etc.

1.5. Criteria for the selection of specific electric loading for electrical machines

- The total number of ampere conductor around the armature periphery is called the total electric loading.
- The number of armature ampere conductor per meter of armature periphery at the air gap is called specific electric loading.

$$ac = \frac{\text{Total armature ampere conductor}}{\text{Armature periphery at airgap}} = \frac{I_z Z}{\pi D}$$

(a) Temperature rise

- The value of specific electric loading is govern by allowable temperature rise of machine. Specific electric loading,

$$ac = \frac{I_z Z}{\pi D} = \frac{I_z \frac{Z}{S}}{\pi D} = \frac{I_z Z_s}{Y_s S}$$

$$I^2R \text{ loss in each slot} = Z_s (I_z)^2 \left(\frac{\rho L}{a_z} \right)$$

$$\text{Heat dissipation surface of slot} = Y_s L$$

Loss dissipated/unit area of armature,

$$q = \frac{Z_s (I_z)^2 \left(\frac{\rho L}{a_z} \right)}{Y_s L} = \frac{Z_s (I_z)^2 \rho}{Y_s a_z} = \left(\frac{I_z Z_s}{Y_s} \right) \left(\frac{I_z}{a_z} \right) \rho = (ac)(\delta)\rho$$

Temperature rise,

$$\theta = qc = (ac)(\delta)\rho c$$

$$ac = \frac{\theta}{\delta \rho c}$$

Where, c is cooling co-efficient

- Higher value of specific electric loading can be selected where higher temperature rise is allowed i.e. machine with the insulation that can withstand higher temperature rise. It also depends on the type of enclosure and cooling techniques employed.

(b) Machine speed

- For high speed machine, higher value of ac can be selected because ventilation is better which will dissipate heat at faster rate i.e. high permissible temperature rise.

(c) Voltage

- For high voltage machine, insulation occupies more space hence space available for conductor is less. So, for this type of machine if high value of ac is selected, it will result in more number of conductor and further it will be difficult to accommodate conductor in slot.

Let,

W_s = Width of slot (m)

d_s = Depth of slot (m)

$$\text{Total area of slot} = S(W_s d_s) = \left(\frac{\pi D}{Y_s} \right) (W_s d_s)$$

$$\text{Total area of conductor in slot} = Z a_z = \left(\frac{(\pi D)(ac)}{I_z} \right) a_z = \frac{(\pi D)(ac)}{\delta}$$

$$\text{Space factor for slot, } S_f = \frac{\frac{(\pi D)(ac)}{\delta}}{\left(\frac{\pi D}{Y_s} \right) (W_s d_s)} = \left(\frac{Y_s}{\delta} \right) \left(\frac{ac}{W_s d_s} \right)$$

$$\therefore ac = \left(\frac{W_s d_s}{Y_s} \right) \delta S_f$$

- For fixed value of slot dimension and number, specific electric loading is directly proportional to space factor of slot. For high voltage machine due to thick insulation over the conductor, value of space factor is small. Hence, it is advisable to select lower value of ac .
- Consequently, space factor depends on shape of conductor. For high voltage machine, current rating is small which allows to choose conductor cross section as circular. The space factor for circular conductor is small compared to rectangular.

(d) Machine size

- In large size machine, more space is available for accommodation of conductor in slot which permits to select higher ac .

(e) Current density

- Higher value of ac can be selected for the machines which has lower current density in the current carrying conductor.

Table 1. 1 Advantages and disadvantages of high specific electric loading

Advantages	Disadvantages
Less volume	High copper loss i.e. less efficiency
Small size	High leakage reactance i.e. poor voltage regulation
Less weight	High temperature rise
Less material cost	High field current in DC machine
Less overall cost	Low stability in synchronous machine

1.6. Criteria for the selection of specific magnetic loading for electrical machines

- The total flux around the armature or stator periphery at the air gap is called the total magnetic loading.
- The average flux density over the air gap of rotating machine is called specific magnetic loading.

$$B_{av} = \frac{\text{Total flux around the airgap}}{\text{Area of flux path around the airgap}} = \frac{p\phi}{\pi DL}$$

- In some of the cases, maximum gap density is selected in design instead of specific magnetic loading.

$$B_g = \frac{\text{Average gap density}}{\text{Ratio of pole arc to pole pitch}} = \frac{B_{av}}{\psi}$$

(a) Maximum flux density in tooth

- Maximum flux density in iron part of machine is directly proportional to average flux density of air gap.

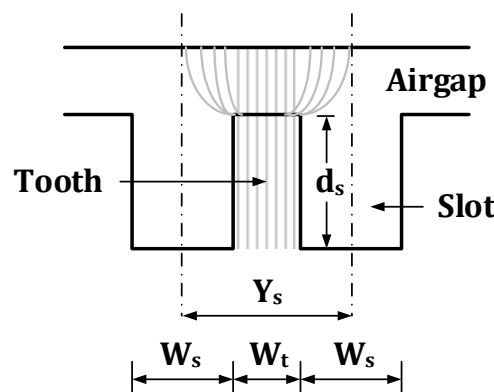


Figure 3. 1 Flux over one slot pitch

Let,

W_s = Width of slot(m)

W_t = Width of tooth(m)

d_s = Depth of slot(m)

Y_s = Slot pitch(m)

$$\text{Flux over one slot pitch} = \frac{p\phi}{s} = \frac{B_{av}\pi DL}{s} = B_{av} \frac{\pi D}{s} L = B_{av} Y_s L$$

$$\text{Flux density in tooth, } B_t = \frac{\text{Flux in each tooth}}{\text{Area of each tooth}} = \frac{B_{av} Y_s L}{W_t L} = B_{av} \frac{Y_s}{W_t}$$

- In salient pole machine flux is concentrated over the pole arc, hence teeth under that pole arc will carry almost flux. It is clear from above equation, that ratio B_t/B_{av} is constant, hence value of B_{av} must be selected such a way that value of B_t does not exceed the specific limit.
- Small machines are designed with parallel sided slot with tapered tooth i.e. width of tooth is not same over the height. Tooth flux density will vary from minimum to maximum over tooth height from larger to smaller tooth width.
- Thus, low value of specific magnetic loading is selected for small machine to compensate flux variation.
- When higher value of average gap density is selected, mmf required for iron part of machine will be very high, which further results in large field ampere-turn, field copper loss and cost of copper.

(b) Magnetizing current

- Magnetizing current depends on the mmf drawn by air gap and iron part of the machine.
- Mmf of air gap is directly proportional to the specific magnetic loading i.e. B_{av} and mmf of iron part is proportional to the value of flux density in it.
- For large value of specific magnetic loading, flux density in iron part is comparatively high and hence iron part works above the knee point of B-H curve i.e. in the saturation region.
- When iron part works in saturation region, it draws excessive mmf and large magnetizing current.

(c) Core loss

- For given specific magnetic loading, core loss increases with the increase in frequency of reversal. Hysteresis loss is proportional to frequency and eddy current loss is proportional to square frequency.
- Hence for high speed DC machine or high frequency AC machine, specific magnetic loading should be selected low in order to minimize core loss.
- For given frequency and flux density, two machines having linear dimension in the ratio of $x:1$ has core loss in the ratio of $x^3:1$ and output in the ratio of $x^4:1$. Thus core loss decreases with increase in size of machine.

Table 1. 2 Advantages and disadvantages of high specific magnetic loading

Advantages	Disadvantages
Less volume	Large mmf i.e. high saturation
Small size	High iron loss
Less weight	High field current in DC machine
Less material cost	High magnetizing current in AC machine
Less overall cost	High flux density in teeth and core
Less copper loss	High temperature rise
High stability in synchronous machine	High magnetic noise

1.7. Criteria for the selection of conducting material for electrical machines

- Three types of conducting materials (i) Low conductivity (ii) High conductivity (iii) Super conductivity are used in electrical applications.
- Low conductivity i.e. high resistivity materials are used for heating devices, thermocouples and resistance.
- High conductivity i.e. low resistivity materials are used for windings of electrical machines and equipments.
- Super conductivity materials drops its resistivity sharply to zero value when the temperature is brought down below transition temperature. Hence, machines with these conductors can be designed with very high value of current density that reduces the size of the machine.
- An ideal conducting material should have
 - Low resistivity
 - Low temperature coefficient of resistance
 - High tensile strength
 - High melting point
 - High resistance to corrosion
 - Capacity to braze, solder or weld for reliable joints
 - High flexibility, ductility and durability
- Best conducting material is silver, next best is copper and then aluminum. For the same resistance and length, cross-sectional area of aluminum is 61% larger than copper and aluminum is 50% cheaper than copper.

Table 1. 3 Property of conducting materials

	Unit	Silver	Copper	Aluminum
Conductivity	----	1.000	0.975	0.585
Resistivity	$\mu\Omega$ -cm	1.460	1.777	2.826
Temperature Coefficient	% per °C	0.337	0.393	0.400
Cost	----	High	Medium	Low

1.8. Criteria for the selection of insulating material for electrical machines

- To avoid any electrical activity between parts at different potentials, insulating materials are used. They are diverse in nature. An ideal insulating material should have
 - High dielectric strength
 - Capacity to withstand high temperature
 - Good thermal conductivity
 - High resistivity
 - Capacity to withstand stresses due to centrifugal forces dynamic or mechanical forces
 - Capacity withstand vibration, abrasion, bending
 - Flexibility and cheap in nature
 - Moisture ingress free nature
 - Immunity to deterioration at higher temperature
 - Low dielectric loss angle i.e. no power consumption

(a) Classification of insulating material based on material type

- **Solid insulations:** Generally used in field winding, armature winding and transformer windings. It can be paper, wood, card board, cotton, jute, silk, rayon, nylon, terelane, asbestos, fiber glass, amber, shellac, polyesters, epoxy, silicon resins, bakelite, teflon, PVC, natural rubber, butadiene, silicone rubber, hypalon, mica, marble, slate, talc chloride, porcelain, steatite, alumina, mineral waxes, asphalt, bitumen, chlorinated naphthalene, enamel etc.
- **Liquid insulations:** Generally used in transformers, circuit breakers, reactors, rheostats, cables and capacitors for impregnation. It can be mineral oil, askarels, pyranols, varnish, french polish, lacquer epoxy resin etc.
- **Gaseous insulations:** Generally used in switches, air condensers, transmission and distribution lines, high pressure cables and neon sign lamps. It can be nitrogen, hydrogen, neon, argon, mercury, sodium vapors, fluorine etc.

(b) Classification of insulating material based on thermal consideration

Table 1. 4 Class of insulation based on temperature

Class	Temperature (°C)	Materials under this class
Y	90	Cotton, silk, paper, cellulose without impregnation
A	105	Oil impregnated cotton, silk, paper, laminated wood, varnished paper
E	120	Synthetic resin enamles, cotton and paper laminates
B	130	Mica, glass fibre, asbestos
F	155	Materials of class B insulation with more thermal resistance capacity
H	180	Glass fiber and asbestos materials and built up mica with appropriate silicone resins
C	>180	Mica, ceramics, glass, quartz and asbestos with resins of super thermal stability

- For small electrical machines, class A and class E insulations are used to reduce cost.

- For large electrical machines, class B and class F insulations are most techno-economical.
- The latest trend is to design large machines with class F insulation and use it for class B temperature rise.
- Class H and class C insulations are costly, hence preferred for special application such as submarines and space craft where cost is not prime criteria.
- No insulating material in practice satisfies all the desirable properties, hence material that satisfies most of the desirable properties must be selected.

1.9. Criteria for the selection of magnetic material for electrical machines

- The property of a magnetic material depend on the orientation of the crystals of the material.
- An ideal magnetic material should have
 - Low reluctance
 - High relative permeability
 - High saturation induction
 - High electrical resistivity
 - Narrow hysteresis loop
 - High curie point
 - High energy product
- Different type of magnetic materials such as diamagnetic, paramagnetic, ferromagnetic, and ferrimagnetic are available for use.
- But only ferromagnetic material has the properties that are well suitable for electrical machines. These materials can be classified as hard magnetic materials, soft magnetic materials, special purpose alloys and amorphous alloys.
- Hard material has large size hysteresis loop and gradually rising magnetization curve. Carbon steel, tungsten steal, cobalt steel, alnico, hard ferrite are the examples of it.
- Soft magnetic material has small size hysteresis loop and a steep magnetization curve. Cast iron, cast steel, rolled steel, forged steel and silicon steel are the examples of it.
- Permeability and resistivity of steel can be improved by adding some percentage of silicon in it. But, if the percentage of silicon is more than 4%, it becomes brittle. These silicon steels are made into laminations of normal thickness of 0.35-0.5 mm.
- Special purpose alloys such as high Nickel Permalloy (iron+molybdenum+copper or chromium), low Nickel Permalloy (iron+silicon+chromium or manganese), Perminvor (iron+nickel+cobalt), Pemendur (iron+cobalt+vanadium) and Mumetal (copper+iron) are used in induction coils, chokes, current transformers and magnetic amplifiers.
- Amorphous alloys are produced by rapid solidification of the alloy at cooling rates of about a million degrees centigrade per second.
- 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 meter wide.

1.10. Heating of electrical machines

- During process of energy transfer in transformer and energy conversion in rotating machine, current flowing in conductor and flux linked in iron part produces the losses among it.
- There losses appears as heat which leads to temperature rise of every part of machine and surrounding atmosphere. Heated part of machine dissipates heat in to the atmosphere by conduction, convection and radiation.

(a) Heat dissipation by conduction

- Heat dissipation through solid part such as conductor, iron and insulation is followed by conduction.

Q_{con} = Heat flow for conduction (Watt)

θ_1 = Temperature of first bounding surface ($^{\circ}\text{C}$)

θ_2 = Temperature of second bounding surface ($^{\circ}\text{C}$)

R_c = Thermal resistance of medium ($^{\circ}\text{C}/\text{Watt}$)

ρ = Thermal resistivity of medium ($^{\circ}\text{C}\cdot\text{m}/\text{Watt}$)

t = Thickness of medium (m)

S = Surface area separated by medium (m^2)

θ = Temperature difference between two bounding surface ($^{\circ}\text{C}$)

Let,

$$Q_{con} = \frac{\theta_1 - \theta_2}{R_c} = \frac{\theta}{R_c}$$

$$\therefore \theta = Q_{con} R_c = Q_{con} \left(\frac{\rho t}{S} \right)$$

(b) Heat dissipation by convection

- Heat dissipation through fluid or liquid medium is followed by convection. It can be of two types, natural convection and artificial convection.

Q_{conv} = Heat dissipated by convection (Watt)

θ_1 = Temperature of emitting surface ($^{\circ}\text{C}$)

θ_0 = Temperature of ambient medium ($^{\circ}\text{C}$)

K_c = Constant depends on shape and dimension of heated body

S = Emissivity due to convection ($\text{Watt}/\text{m}^2\cdot^{\circ}\text{C}$)

λ_{conv} = Specific heat dissipation by natural convection ($\text{Watt}/\text{m}^2\cdot^{\circ}\text{C}$)

λ'_{conv} = Specific heat dissipation of blasted surface ($\text{Watt}/\text{m}^2\cdot^{\circ}\text{C}$)

V = Relative velocity of cooled surface and airblast (m/s)

K_v = Constant depends on uniform or nonuniform blast

For natural convection,

$$Q_{conv} = K_c (\theta_1 - \theta_0) S = \lambda_{conv} (\theta_1 - \theta_0) S$$

For artificial convection,

$$Q_{conv} = K_c (\theta_1 - \theta_0) S = \lambda'_{conv} (\theta_1 - \theta_0) S = \lambda_{conv} (1 + K_v \sqrt{V}) (\theta_1 - \theta_0) S$$

(c) Heat dissipation by radiation

- Heat dissipation through air or gases medium is followed by radiation. The rate of heat dissipation through radiation depends on temperature, color and roughness of medium.

Q_{rad} = Heat dissipated by convection (Watt/m²)

θ_1 = Temperature of emitting surface (°C)

θ_0 = Temperature of ambient medium (°C)

T_1 = Absolute temperature of emitting surface (K)

T_0 = Absolute temperature of ambient medium (K)

e = Co-efficient of emissivity

$$Q_{rad} = 5.7 \times 10^{-8} e (T_1^4 - T_0^4) = 5.7 \times 10^{-8} e (\theta_1^4 - \theta_0^4)$$

Where,

$$T_1 = \theta_1 + 273$$

$$T_0 = \theta_0 + 273$$

1.11. Cooling of electrical machines

- Cooling is a process by means of that heat generated in electrical machines are given up to the coolant. It keeps machine output stable, increases the efficiency and protects the parts of machine from thermal damage.
- Initially heat is transferred to primary coolant by increasing its temperature. The heated primary coolant can be replaced by same coolant at low temperature or can be cooled by secondary coolant through heat exchanger.

(a) Cooling based on origin of cooling

- Self-cooling:** Electrical machine being cooled by air due to rotation of parts or due to temperature gradient between two parts.
- Natural cooling:** Small electrical machines are being cooled by natural means i.e. flow of air stream into the ventilating ducts by means of fan mounted on machine shaft.
- Separate cooling:** Large electrical machines are being cooled by separate cooling i.e. other cooling medium that is not the part of machine.

(b) Cooling based on manner of cooling

- Open circuit ventilation:** Heat is dissipated directly to the cooled air, that is continuously replaced.
- Surface ventilation:** Heat is dissipated by the cooling medium through external surface of totally enclosed machine.
- Closed circuit ventilation:** Heat is dissipated to the cooling medium through an intermediate cooling medium circulating in closed circuit in a machine via cooler.

- **Liquid cooling:** Heat is dissipated to the water or cooling fluid in which machine is fully immersed or part of machine is immersed.
- **Inner cooling of winding:** Winding heat is dissipated to the gas, hydrogen or water that is flowing internally through the conductors or coil.

1.12. Enclosures of the rotating machines

- Enclosures are the surrounding case constructed to provide protection to the electrical machine against the incidental contact or environmental condition.
 - Machine with enclosures cannot have free ingress of air which results in temperature rise of it. Higher temperature means reduction in output. Thus, ventilation or cooling system of a machine depends on enclosures.
- (a) Open type:** Machine parts are directly in contact with outside ambient air i.e. no protection against dust, dirt, moisture or other environmental condition.
 - (b) Protected type:** Machine main parts are protected with end covers but large openings are provided in the cover of ventilation.
 - (c) Screen protected type:** Machine main parts are protected with end covers but large openings are covered with wire mesh in order to prevent large forging particles.
 - (d) Drip proof type:** Machine main parts are protected with ventilation opening in end covers through hanging bowls. This is used for the machine installed in damp condition.
 - (e) Totally enclosed type** Machine main parts are protected with totally enclosed cover. Dirt, dust or foreign particle cannot enter into the machine.
 - (f) Flame proof type:** Machine parts are protected with flame proof enclosures that withstands any explosion of gas inside the machine without transmitting the flame to the outside. Mainly used in coal mines or explosive atmosphere.