Basic Consideration

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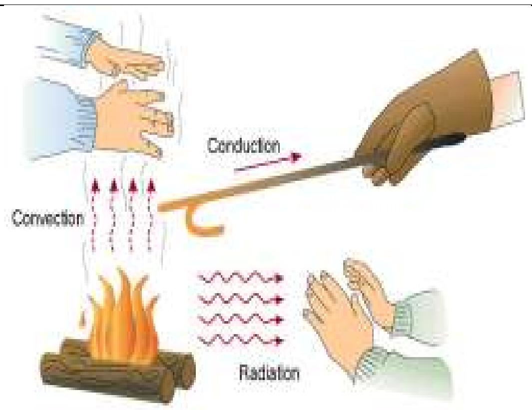

Curtesy: www.ukinsulations.co.uk

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References:

1. Notes by Dr. R. C. Goel
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3. Principles of Electrical Machine Design by R.K Agarwal
4. VTU e-Learning
5. www.google.com
6. www.wikipedia.org

STANDARDS AND STANDARDIZATION:

Standards: The equipment should satisfy certain specified norms with respect to quality, performance, temperature rise etc.

Each country lays down its own standards e.g.

- Indian standards: Indian standard institution (ISI)
  (Now BIS: Bureau of Indian standard)
- British standard: British standard institution (BSI)
- American standard: American standard association (ASA)
- German standard: Deutsche Industries Norms (DIN)
- International standard : International Electro-technical Commission (IEC)
  (Now two IEC+ISO: International organization for standardization)

It was created jointly by various countries and the standards made by IEC are acceptable globally.

Standardizations: The process of creating, implementing or using a standard is known as standardization. It means laying down of specification, specifying rating, maintaining same quality of products. The Indian Standard Institute has laid down preferred ratings for 3-Phase distribution transformers e.g.

Rating: 15 KVA, 25KVA, 40KVA 50KVA, 63KVA, 80KVA, 100KVA etc.

Voltage ratio: 1100/433 , 3300/433V, 6600/433V

Connection: Δ/Y

Advantages of Standardizations:

- Ease of manufacturing.
- A number of items with same specification can be made resulting in cheaper value.
- Spares can be interchangeable.

Indian Standard Code:

		Number	year	
IS	:		:	for electrical conductors
IS	:		:	transformers
IS	:	3454	: 1966	induction motors

SPECIFICATION:

- **For 3-phase transformers**

-Rating	KVA/MVA
-Voltage ratio	V1/V2
-frequency	50 Hz
-current ratio	I_1/I_2
-connection	(Δ- λ/ λ-Δ / Δ-Δ /λ-λ /Δ-zig -zag)

- **For 3-phase Induction motor**

-rating	KW
-voltage	
-Full load current	
-no load current	
-frequency	
-speed	
-connections	
-temperature rise	
-Rotor	Squirrel cage (a) Single cage (b) Double cage
	Slip ring
-starting method	DOL
	Delta/Star
	Autotransformer starting for slip ring motor, Rotor resistance starter
-class of insulation	

PHILOSPHY OF COMPUTER AIDED DESIGN ADVANTAGES AND LIMITATIONS:

The design of electrical machine involves large number of iterative calculations based on numerous assumed data like electric loading, magnetic loading, frame size etc.It is further desired that the design should be optimum and to make optimum design one has to take help of great analytical capabilities and decision making capability of the digital computer based on instruction given in the programs or softwares.

Limitations:

The digital computer neither has an intuition nor it feel about the designs and the best it work on exact instructions and the commands given by the designer. The best possible design can be obtained by the combination of the designer and the great analytical capabilities of the digital computer.

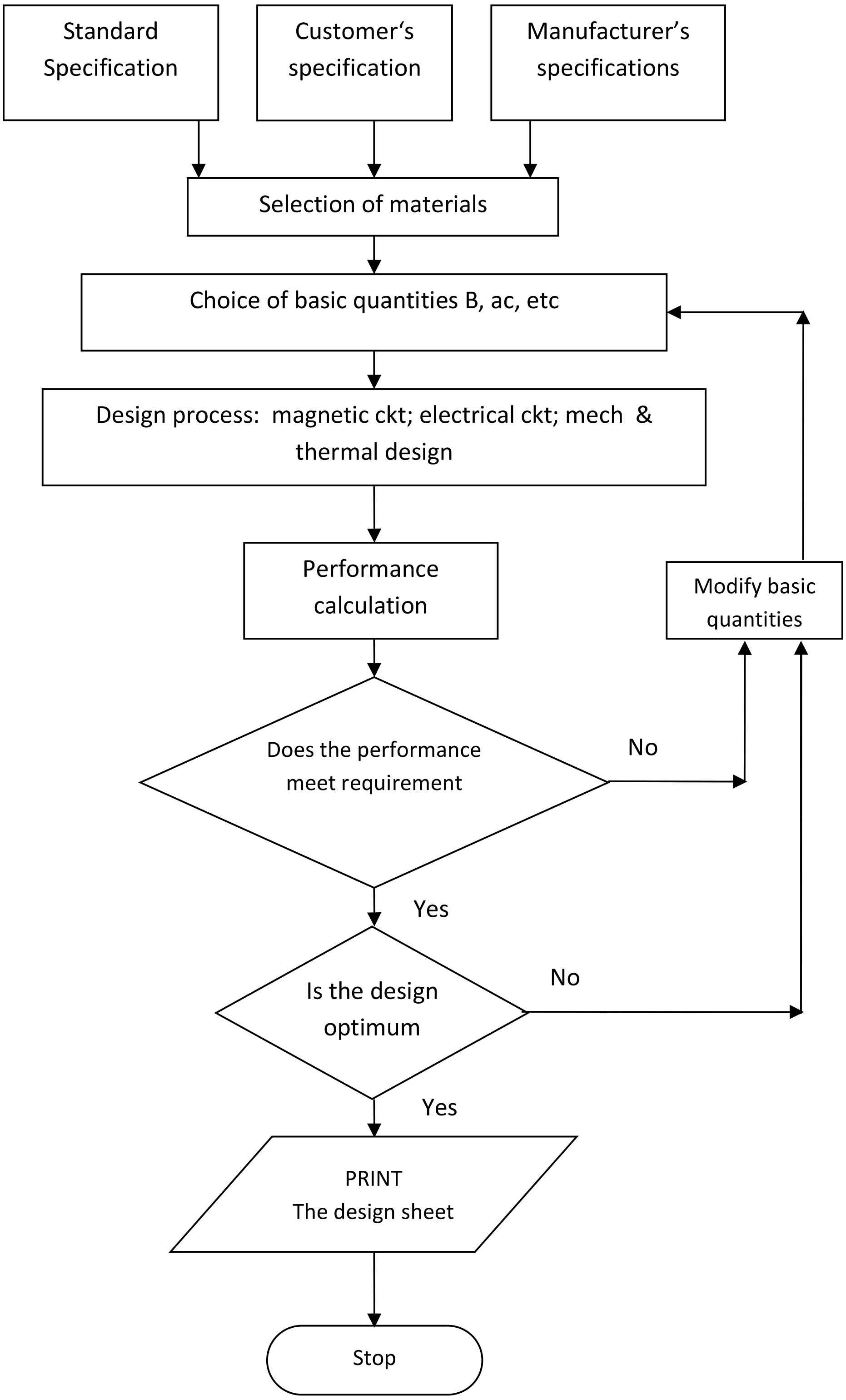
Computer Aided Design of Electrical Machines:

1. Standard specifications
2. Customer's specifications
3. Manufacturer's specifications

Taking into consideration of above specifications, flow chart of generalized CAD of electrical machines is shown on the next page.

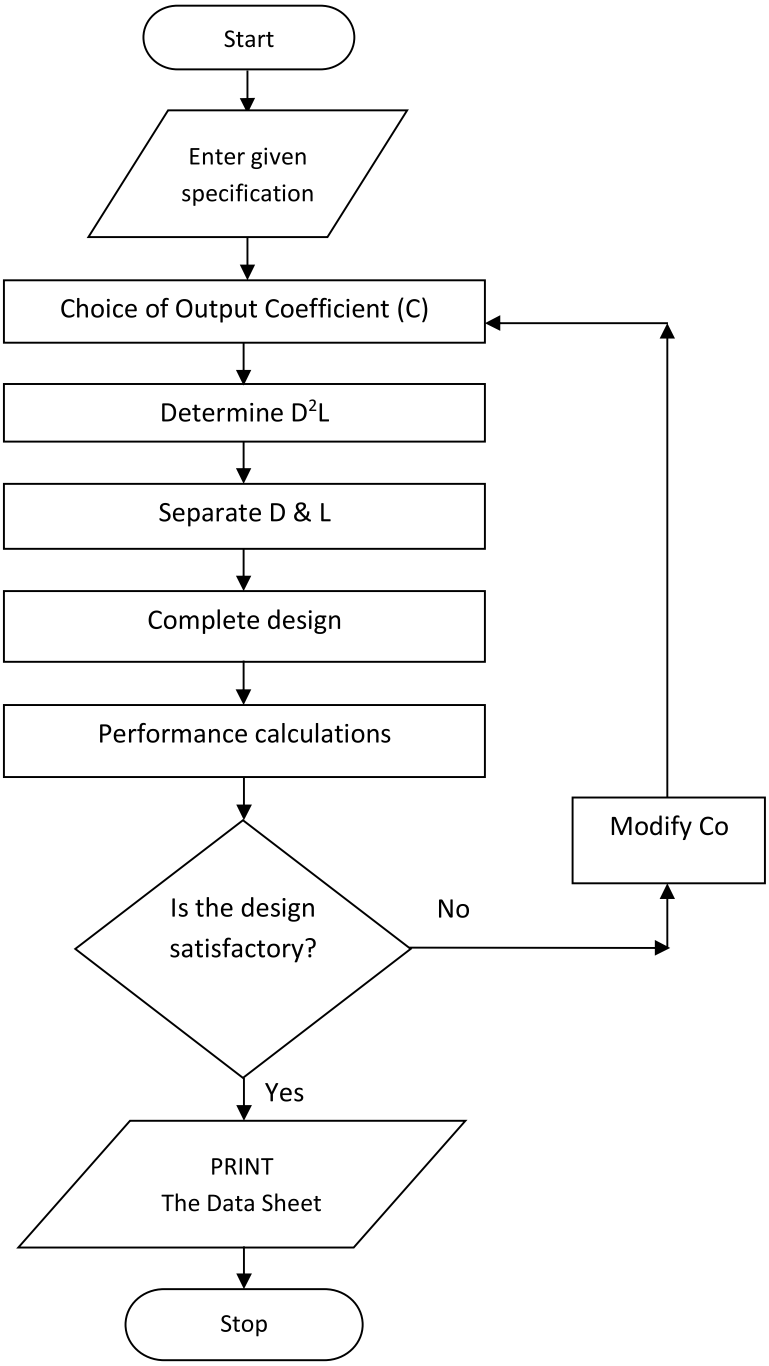
The computer aided design may be classified into three categories (3 methods)

1. Analysis
2. Synthesis
3. Hybrid



Flow chat for generalized computer aided design of electrical machines

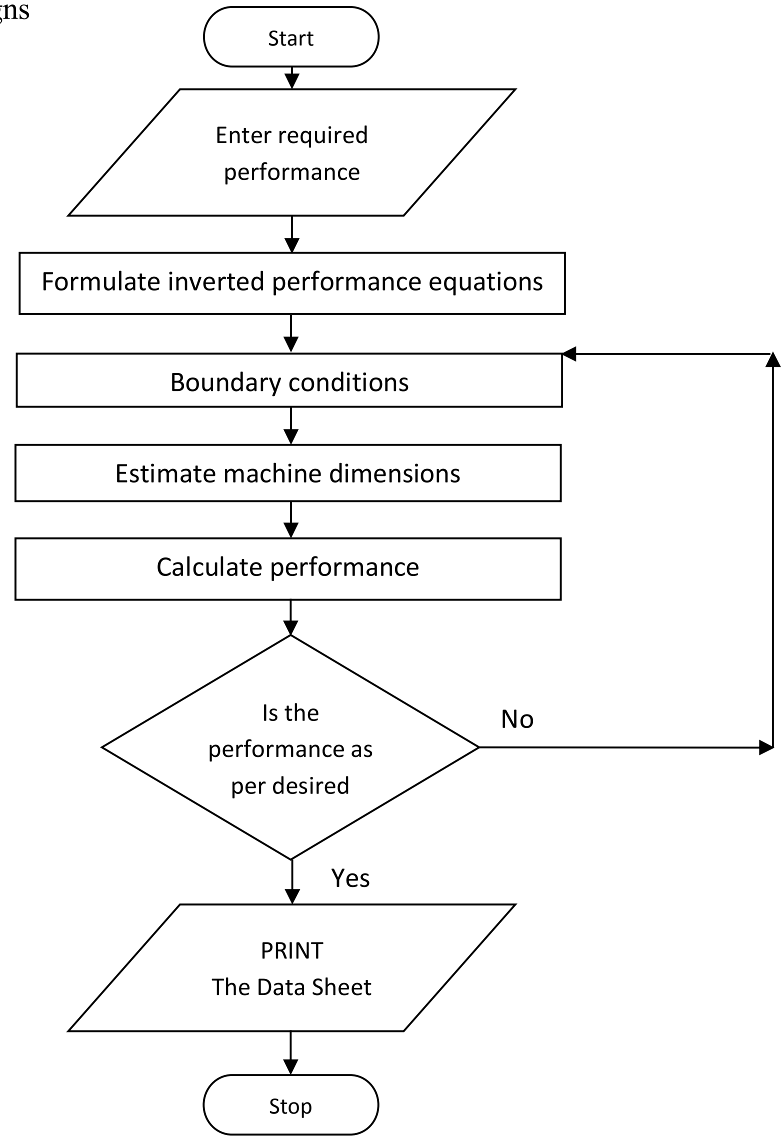
Analysis Method: We start with machine specifications choose basic quantities, find out machine dimensions through the design process and then we calculate the performance, if the performance is not satisfactory, we modify the basic quantities.



Analysis Method

Synthesis Method: It is the inverse of analysis method. We start with the performance and formulate inverted performance equations in differential form and assume boundary conditions and determine the machine dimensions and performance.

Through it is best approach for design but most complicated in nature and sometimes leads to unfeasible designs



Synthesis Method

Hybrid Method: It is a combination of analysis and synthesis. We may do most of the design with analysis and rest by synthesis. It gives more practical designs.

MATERIALS USED IN CONSTRUCTION OF ELECTRICAL MACHINES:

1. **Conducting materials:** They should have resistance as low as possible
   (a) Silver : used in contacts
   (b) Copper: It is generally used in windings of machines
   (c) Aluminum:
2. **Magnetic materials:** Materials which can be magnetized are called magnetic materials.
   (a) Diamagnetic material: Relative permeability slightly < 1=> Non magnetic
   i.e Silver, copper , water etc so not used in as magnetic materials.
   (b) Paramagnetic material: relative permeability slightly > 1=> Non magnetic
   i.e Aluminum, Air etc so not used in as magnetic materials
   (c) Ferromagnetic material: Relative permeability is very high.
   i.e Iron, Silicon steel, cobalt, Nickel etc so they are used as magnetic materials for construction of electrical machines. They are again classified as:
      i. Hard magnetic materials
      ii. Soft magnetic materials
   (d) Electrical sheet steel: Silica is added in iron. (Si 0.3 to 5%). Silica improves magnetic properties of iron i.e ageing, eddy current loss, hysteresis loss etc .
   Electrical sheet steel may be
      i. Dynamo grade steel: Low silicon content
      ii. HRGO
      iii. CRGO
   These materials are available in the marked as the following names
   E_{23O}, E_{31O}, E_{12O}, E_{21} etc
   1st Subscript means quantity of Si
      1=> low
      2=> average
      3=> above average
      4=> high
   2nd Subscript means iron loss
      1=> low
      2=> average
      3=> high
   3rd Subscript means CRGO/HRGO
      O=> CRGO
      No subscript=> HRGO

Note: Earlier thickness of laminations were 0.35 to 0.5 mm but now thickness of laminations are 0.14 to 0.28 mm

3. **Insulating materials:** Properties are
   (a) Flexibility
   (b) Ability to withstand high temperature
   (c) Good thermal conductivity
   (d) Good dielectric strength
   (e) Good mechanical strength
   (f) Withstand moisture
   (g) Less aging and decay
   (h) Easily availability and economical

Classification of insulating materials (As per IS: 1271:1958):

S. No	**Class**	**Materials**	**Maximum Working Temperature (^{0} C)**
1.	Y	Cotton, Silk, Paper & Similar organic materials when neither immersed in oil nor impregnated	90^0
2.	A	Class Y materials when immersed in oil or impregnated	105^0
3.	E	Some of class A materials which can withstand high temperature	120^0
4.	B	Mica, glass fiber, asbestos with suitable bonding substances	130^0
5.	F	Some of class B materials which can withstand high temperature	155^0
6.	H	Glass fiber, Asbestos materials, built up mica with silicon resins	180^0
7.	C	Mica, ceramics, glass, quartz without binders or with silicone resins of higher thermal stability	$>180^0$

MODES OF HEAT TRANSFER

Heat is transferred to the surrounding medium by the followings methods:-

1. Conduction
2. Radiation
3. Convection

Conduction: The solid parts of the machines transfer heat to the outside surface by the means of conduction. The quantity of heat transfer by means of conduction is given by:

$$Q_{conduction} = \frac{\theta_1 - \theta_2}{R_c} \qquad Watt \; -------- (1)$$

Where

θ_1 and θ_2=temperature of two boundary surfaces

R_c =Thermal resistance of conducting medium

$R_c = \rho \frac{l}{s} = \frac{1}{\sigma} \frac{l}{s}$ Unit is thermal ohms

Radiation: The heat dissipated by radiation from the surface depends upon its temperature and other characteristics like color, roughness etc..

In case of conduction and convection the heat transfer takes place through a medium but in radiation heat transfer involves mechanism of propagation of electromagnetic energy.

For the case of very small spherical radiating surface inside a large and black spherical shell, the heat radiation is given by Stefan Boltzmann law i.e.

$$Q_{radiation} = 5.7 \times 10^{-8} \times e(T_1^4 - T_2^4)S \qquad Watt \qquad ------ (2)$$

Where

e=coefficient of emissivity

e=1, for perfect black body

e<1 , for other body

T_1 *and* T_2 are absolute temperature of emitting surface and ambient medium(K)

S=Surface area (m^2)

$$Q_{radiation} = 5.7 \times 10^{-8} e(T_1 - T_2)(T_1^3 + T_1^2 T_2 + T_1 T_2^2 + T_2^3)S$$
$$Q_{radiation} = 5.7 \times 10^{-8} e(T_1 - T_2)T_r S \quad Watt -------- (3)$$

And $(T_1 - T_2) = [(\theta_1 + 273) - (\theta_2 + 273)]$

$$T_r = (T_1^3 + T_1^2 T_2 + T_1 T_2^2 + T_2^3)$$

θ_1 and θ_2 =Temp of emitting surfaces and ambient medium in ℃

$$Q_{radiation} = 5.7 \times 10^{-8} e\theta S T_r \quad Watt$$
$$Q_{radiation} = \lambda_{radiation} S\theta \quad Watt \qquad ------(4)$$

Where,

$$\lambda_{radiation} = 5.7 \times 10^{-8} e T_r = Specific\ heat\ dissipation\ radiation(\frac{Watt}{m^2 0_C})$$

Convection: Fluid(liquid or Gas) particles coming in contact with hot body becoming lighter and rises giving place to cooler particles thereby creating a thermal heat and consequent circulation. This process is called as natural or artificial convection such as blowing air over a hot body by fan. It is of following types

1. **Natural Convection:** The amount of heat transferred is

$$Q_{convection} = K_c(\theta_1 - \theta_2)^n S \ Watt \quad -------- (5)$$

Where K_c=a constant depending on the shape and dimension of hot body

S=surface area (m^2)

n=a constant depending on the shape and dimension of hot body

=1 to 1.2

$$\theta_1 = Temp.of\ emitting\ surface\ (℃)$$

$$\theta_2 = Temp.of\ ambient\ surface\ (℃)$$

put n=1 in equation (5)

$$Q_{convection} = K_c \Theta S \ Watt$$

$$Where, \Theta = (\theta_1 - \theta_2)$$

$$Q_{convection} = \lambda_{convection} S\Theta ---------- (6)$$

$$\lambda_{convection} = Specific\ heat\ dissipation\ due\ to\ convection\ (W/m^2)$$

2. **Artificial or forced Convection:**

For this $Q_{convection}$ is same as given by equation (6) with

$$\lambda'_{convection} = \lambda_{convection}(1 + K_v\sqrt{V}) \qquad \frac{Watt}{m^2 °C}$$

Where

K_v=constant depends upon whether the blast is uniform or non uniform

=1.3 for uniform blast

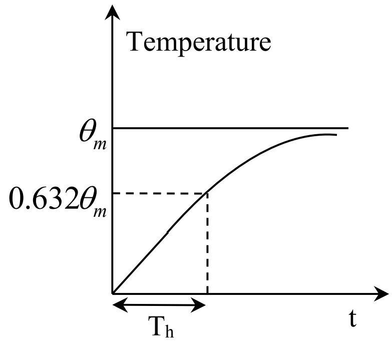
V=relative velocity of cooled surface and air blast

So $Q'_{convection} = \lambda'_{convection} S\theta$

THERMAL STATE IN ELECTRICAL MACHINES:

1. **Heating:** The temperature of machine rises when it is run under steady load condition starting from cold condition.
   Heat produced = heat stored in the parts + Heat dissipated
   Temperature rise of the machine at any time't'

$$\theta = \theta_m\left(1 - e^{-t/T_h}\right) \qquad \text{----------- (1)}$$



Temperature rise curve
(Exponential Rise)

Where

θ_m =Final steady temp rise while heating (^{0}C)

t = time (Sec)

T_h = Heating time constant (Sec)

➢ **Heating time constant:**

Put t = T_h in equation (1)

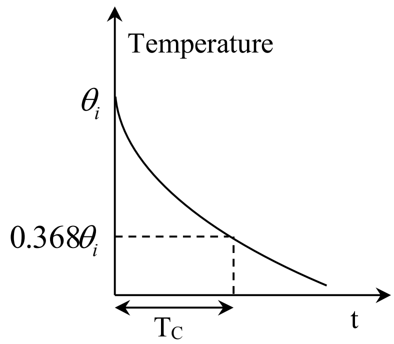
$$\theta = \theta_m\left(1 - e^{-1}\right)$$

$$\theta = 0.632\theta_m$$

So heating time constant is defined as the time taken by the machine to attain 0.632 time of its final steady temperature.

2. **Cooling:** If the machine is shut down, no heat is produced and machine will starts cooling.
   So the temperature of machine

$$\theta = \theta_i e^{-t/T_C} \qquad \text{----------- (2)}$$



Temperature decay curve

Where

θ_i =Initial temp rise over ambient medium (^{0}C)

T_C = Cooling time constant (Sec)

➢ **Cooling time constant:**

Put t = T_C in equation (2)

$$\theta = \theta_i e^{-1}$$

$$\theta = 0.368\theta_i$$

So cooling time constant is defined as the time taken by the machine for its temperature rise to fall 0.368 time of its initial value.

Quantity of cooling medium:

Let Q = Losses to be dissipated (KW) = Qx10^3 W = Qx10^3 J/Sec

θ_i = Inlet temp of cooling medium (^{0}C)

θ = Temp rise of cooling medium (^{0}C)

H = Barometric height (mm of mercury)

P = Pressure (N/mm^2)

1. **Air:** We know heat carried away per sec

$$\text{Heat/Sec(Q - J/Sec)} = \text{Weight of air/Sec(Kg/Sec)} \times \text{Specific heat(C}_P\text{ - J/Kg}^0\text{C)} \times \text{temp rise(}^0\text{C)}$$

So

$$\text{Weight of air} = \frac{Q \times 10^3}{C_P\theta} \quad \text{Kg/Sec ---------- (1)}$$

Let volume of 1 Kg air at NTP (0^0C i.e. 273 K & 760 mm of Hg) is V m^3.
So volume of air required at NTP

$$\text{Volume of air} = \frac{Q \times 10^3}{C_P\theta} V \quad \text{m}^3\text{/Sec}$$

At actual working conditions

Temp of air $= \theta_i{}^0C = (\theta_i + 273)^0 K$

Pressure = H mm of Hg

Apply Kelvin's law

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \text{ ---------- (2)}$$

So volume of air under actual working conditions

$$V = \frac{Q}{C_P\theta} V \times \frac{\theta_i + 273}{273} \times \frac{760}{H} \times 10^3 \quad m^3/Sec \text{ ---------- (3)}$$

- **For dry air**

  C_P = 0.2375 cal/ gm- ^{0}C

  =0.2375x4.18x1000 J/Kg- ^{0}C

  =995 J/Kg- ^{0}C (Watt-sec/Kg- ^{0}C)

  V = 0.775 m^3

Note:
1 Cal=4.18 Joules
=4.18 Watt-Sec

Put in equation (3)

$$V_a = 0.78\frac{Q}{\theta}\times\frac{\theta_i + 273}{273}\times\frac{760}{H} \qquad m^3 / Sec$$

- Power required for blowing air at a rate of V_a m^3/ Sec at pressure of P N/m^2

=PV_a Watt

So power required by fan for blowing air

$$P_f = \frac{PV_a}{\eta_f}\times 10^{-3} \qquad Kw$$

η_f = Efficiency of fan

2. **Hydrogen:**

For Hydrogen

C_P = 3.4 Cal/ gm ^{0}C

= 3.4x4.18x1000 J/Kg ^{0}C

=14.21 J/Kg ^{0}C

V = 11.3 m^3

Put in equation (3)

$$V_h = 0.8\frac{Q}{\theta}\times\frac{\theta_i + 273}{273}\times\frac{760}{H}\times 10^3 \qquad m^3 / Sec$$

3. **Water:**

C_P = 4.18x10^3 J/Kg ^{0}C

Put in equation (1)

Volume of water required per sec

$$= \frac{Q}{4.18\times\theta} \quad Kg / Sec = 0.24\frac{Q}{\theta} \quad Kg / Sec \;\; or \;\; l / \sec$$

4. **Oil:**

Amount of oil required per sec

$$= 0.24\frac{Q}{(0.4 \rightarrow 0.5)\theta} \quad l / Sec$$

Example 1: Find the amount of cooling air required per second at the inlet temperature of 25^{0}C for a 25000 KVA alternator working at full load. The efficiency is 96% and the power factor is 0.87. The temperature of air coming out of machine is 50^{0}C.Cp=14.17 V=834. Air pressure is 760 mm of mercury.

Solution:

Output in KW =KVAxP.F =25000x0.87=21750 KW

Input in KW =Output/Efficiency =21750/0.96 = 22656.25 KW

Losses in KW Q =Input power- Output power =906.25 KW

Using standard values for specific heat and weight of air, quantity of air

$$V_a = 0.78\frac{Q}{\theta}\times\frac{\theta_i + 273}{273}\times\frac{760}{H} \qquad m^3/Sec$$

$$V_a = 0.78\frac{906.25}{(50-25)}\times\frac{25+273}{273}\times\frac{760}{760} \qquad m^3/Sec$$

$$V_a = 30.86 \qquad m^3/Sec$$

<u>Cooling and ventilation of rotating machines:</u> A process by means of which heat resulting from losses occurring in a machine is given up to a primary coolant by increasing its temperature. The heated primary coolant may be replaced by new coolant at lower temperature or may be cooled by a secondary coolant in some form of heat exchanger.

Types of cooling systems:

1. **Natural cooling:** No fans etc
2. **Self cooling:** Fan is attached to the rotor shaft
3. **Separate cooling:** Fan is driven by separate machine.

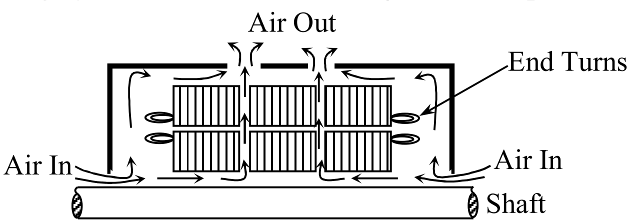
The cooling of electrical machines by means of an air stream is called ventilation of machines.

Types of ventilation

1. **Open circuit ventilation:** When machine is open from both sides
    a. Induced ventilation: Fan sucks the hot air from machine.
    b. Forced ventilation: Fan pushes the cool air into the machine
2. **Closed circuit ventilation:** In this heat is transferred through an intermediate ventilating medium normally air or H_2 circulating in closed circuit.
3. **Surface ventilation:** The heat is transferred from inside of the machine by cooling medium to the external surface of a totally enclosed machine. The external surface is being cooled by natural means or by blowing air by fan.

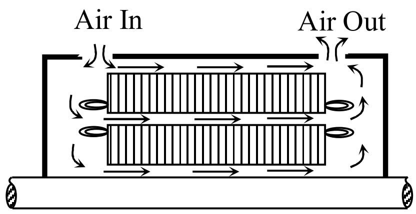
Again ventilating system can be further classified in three types

1. **Radial Ventilating system:** Radial ventilating ducts are provided as shown in following diagram.



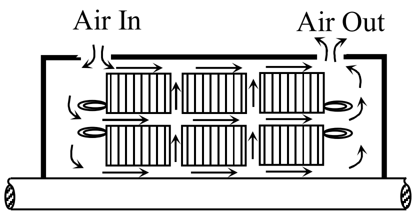
Radial Ventilating System
(Fan may also be provided on shaft)

2. **Axial ventilating system:** Axial ventilating ducts are provided as shown in following diagram.



Axial Ventilating System

3. **Combined radial and axial ventilating system:**



Combined Radial & Axial Ventilating System

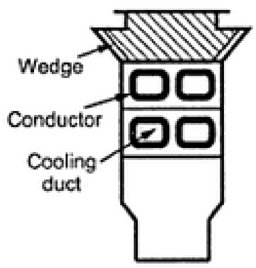
<u>Direct Cooling:</u> In this type of cooling the conducting material has direct access with the coolant.

Advantages:

- Due to quick transfer of heat rating of the machine can be considerably increased.
- Since coolant comes in direct contact with the conductor, the temperature gradient across slot insulation, teeth and surface barrier are considerably reduced.

Generally hydrogen (Gas) & water are used for direct cooling (Sometimes oil also)

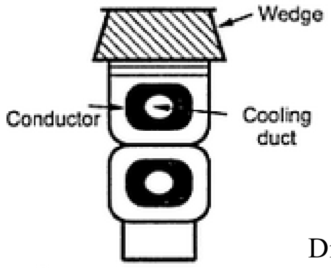
1. **Direct H_2 (Gas) Cooling:** In this both stator and rotor conductors are made hollow. Hydrogen is pumped through these conductors from one end to the other.



Direct H_2 (Gas) Cooled

2. **Direct water cooling (Distilled water):** Direct water is also good because of
    a. Better heat transfer capacity of water
    b. Viscosity of pure water is low
    c. Less pressure is required for maintaining the flow of water.

Turbo alternators of the highest possible ratings use to have hydrogen cooled stator core and direct water cooled stator and rotor windings.



Direct Water Cooled

<u>Frame and frame size:</u> Frame is the outer (external structure) body of the machine in which stator core is fitted. It serves the following purposes.

1. Houses the core and windings
2. Protects the live and moving parts
3. Torque developed is transmitted through shaft and bearing. So frame should be strong enough to bear twisting torque, shocks and vibrations.
4. Provides ventilation & cooling.

Frame are suitably designed and made for rotating like induction motor, synchronous machines, DC machines etc.

In induction motor airgap length is very small; hence frame must be very strong and rigid so that airgap remains uniform. Any variation in airgap length will cause sufficient unbalanced magnetic pull.

There are two types of frames

1. Die-cast frame
2. Fabricated frame

1. **Die-cast frame:** They are used for machines of rating up to 50 Kw. They are die cast having ribs which are axial inside.

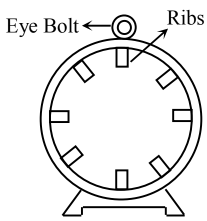


Fig.1a Die Cast Frame: very small M/Cs (1-2Kw)

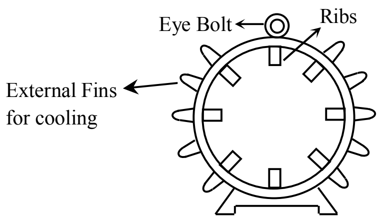


Fig.1a Die Cast Frame: very small M/Cs (1-2Kw)

2. **Fabricated frame:** They are made for medium and large rating machines. Small length cylinders may be used as frames or steel plates may be welded together to from the frame.

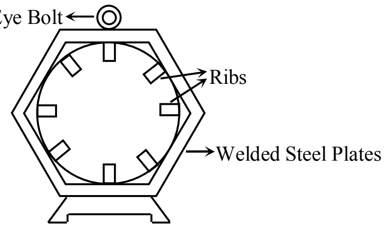


Fig.2b Fabricated Frame

They have internal ribs upon which stator core is fitted and provides space for cooling between the frame and stator core.

The suitable end covers (with bearings) are rigidly fitted. In this type of frame there is greater flexibility of frame design and can easily modified.

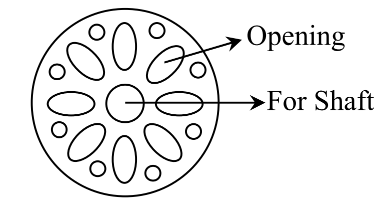
Frame Size: The manufacturing company may have charts of the frame sizes available. In design corresponding to D^2L we may readily obtain details of inner and outer stator dia, air gap length, rotor external dia and length of the machine. There may be alternative frame sizes corresponding to same D^2L. We may select a suitable frame size depending on our or customer requirement. These frames are in conformity with IS codes.

While standardizing the frame size there may be two considerations

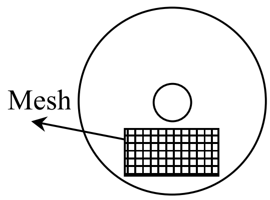
1. Height of the shaft from base
2. Length of the shaft. These lengths are usually designated as short, medium and long represented by
    a. S = Short
    b. M = Medium
    c. L = Long

Enclosures for Induction Motors: They are classified as

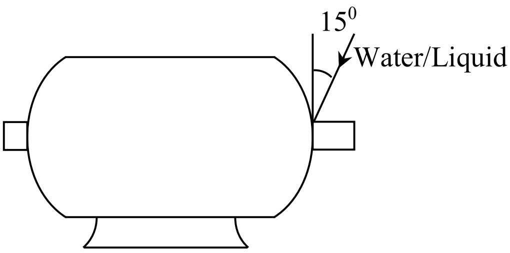
1. **Open type:** In open type enclosures, no protection (against dust, dirt or large foreign bodies) is provided to stator and rotor of electrical machine. The ends of machines are directly in contacts with outside ambient air, resulting in good cooling.
2. **Semi closed type:** The end covers with large opening for ventilation are provided for the machine. The cooling will be somewhat lesser as compared to open type.
    a. **Wire mesh:** Dust etc will not enter in the machine.
    b. **Drip proof:**
    c. **Splash proof:**



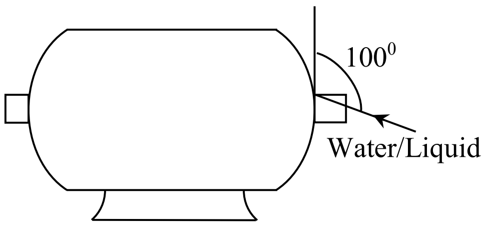
Semi-closed end Cover



Semi-closed end cover



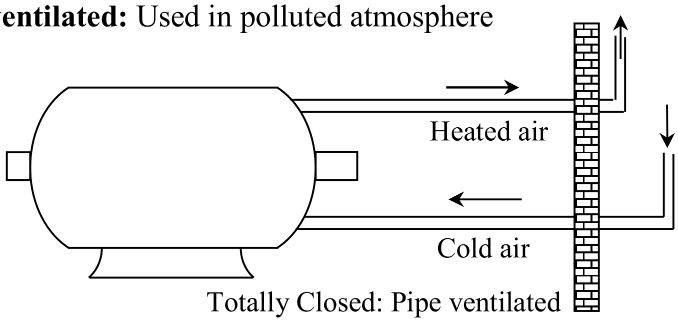
Semi-closed drip proof



Semi-closed splash proof

- In open and semi-closed type enclosures, a number of fan blades may be attached with the shaft to increase cooling of the machine.

3. **Totally closed type:**
   a. **With large frame to provide cooling:** Since the cooling air gets confined to the enclosure of the machine, effective cooling is reduces. For this purpose we can increase the frame size to allow sufficient air for cooling.
   b. **Pipe ventilated:** Used in polluted atmosphere



Totally Closed: Pipe ventilated

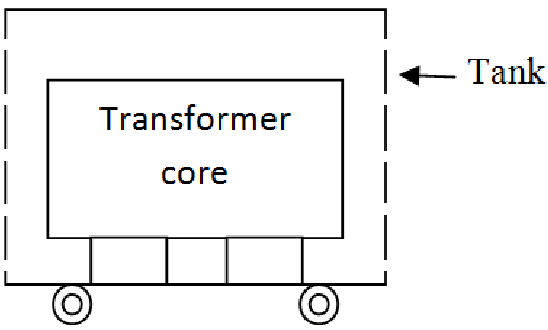
   c. **Water proof:** Water resistance
   d. **Submersible in water or fluid:** Under water or fluid
   e. **Alkali and chemical resistant:** Used in chemical factories
   f. **Explosion proof:** Used in mines

Cooling system design of transformer:

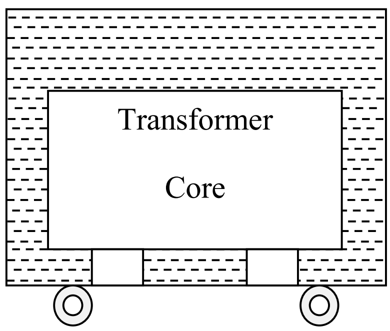
Methods are

Natural cooling:	AN: Air Natural ON: Oil Natural OFN: Oil forced cooled with natural air	δ=1.5 to 2.3 A/mm^2
Artificial:	AB: Air Blast OB: Oil which is cooled by air last OFB: Oil forced which is cooled by air blast	δ=2.2 to 4 A/mm^2
Water Circulation:	OW: Oil cooled by water circulation OFW: Oil Forced & cooled by water circulation	δ=5 to 7 A/mm^2

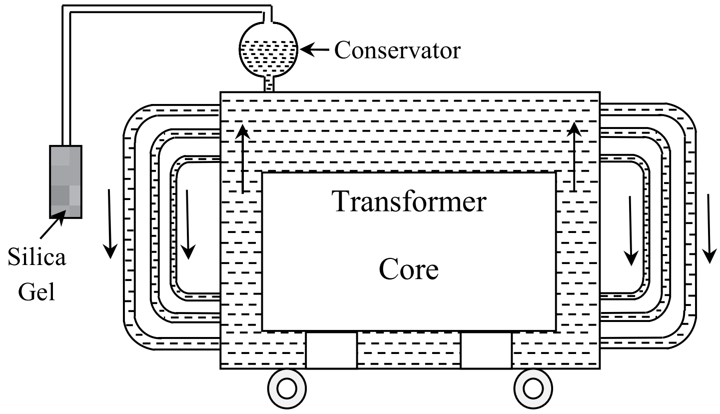
- **Transformer of rating up to 5 KVA:** Air natural cooling is provided



- **Transformer of rating up to 30 KVA:** Oil natural cooling is provided



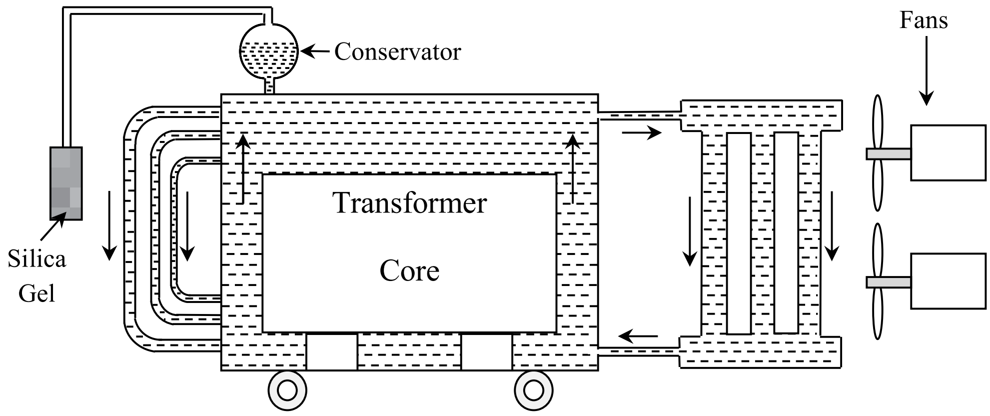
- **Transformer of rating up to 3 MVA:** External cooling tubes are provided



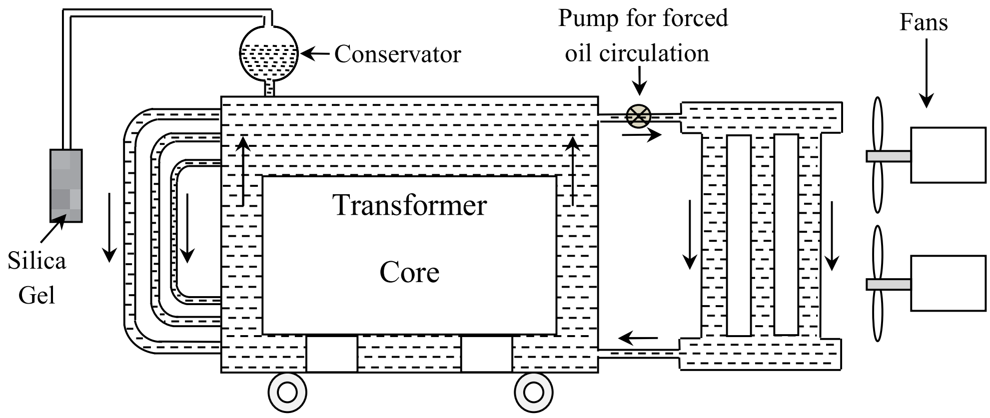
Note:

(i) Conservator is generally filled up to 1/3rd only.
(ii) Silica gel absorbs moisture from the transformer oil during the breathing process.
(iii) Oil flow is shown by the arrow.

- **Transformer of rating up to 10 MVA:** External radiator with fans is provided



- **Transformer of rating up to 30 MVA:** External radiator with pump for forced oil circulation is provided



- **Transformer of rating above 30 MVA:** External radiator which is cooled by secondary coolant (water) as shown in following figure is provided