A HELPLINE FOR COURSE IN ELECTRICAL MACHINE DESIGN

Previous Years Question Papers

(Fully Solved) K.U.K., C.D.L.U., GJUS&T,

Hisar & other Universities

for

B. Tech. EE & EEE 7th Semester students

by:

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ELECTRICAL MACHINE DESIGN

(EE-401E, ET-401E)

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ELECTRICAL MACHINE DESIGN

EE-401-E / ET-401-E

L	T	P/D	Total	
3	1	-	4	External : 100/ 70 Marks
				Internal : 50/ 30 Marks
				Duration : 3 Hrs.

UNIT I

GENERAL: General features & limitations of electrical machine design, types of enclosures , heat dissipation, temperature rise, heating & cooling cycles, rating of machines, cooling media used & effect of size and ventilation.

DC MACHINES: Output equation, choice of specific loadings, choice of poles and speed, Design of conductors, windings, slots field poles, field coils, commutator and machine design.

UNIT II

TRANSFORMERS: Standard specifications, output equations, design of core, coil, tank and Cooling tubes, calculation of circuit parameters, magnetizing current, losses and efficiency, Temperature rise and regulations from design data.

SYNCHRONOUS MACHINES: Specifications, ratings and dimensions, specific loadings, main dimensions, low speed machines, turbo generators, armature conductors, cooling.

UNIT III

INDUCTION MOTORS:

Three Phase Induction Motor: Standard specifications, output equations, specific loadings, main dimensions, conductor size and turns, no. of slots, slot design, stator core, rotor design, performance calculations.

Single Phase Induction Motor: output equations, specific loadings, main dimensions, design of main and auxiliary winding, capacitor design, equivalent circuit parameters, torque, efficiency.

UNIT IV

Computer Aided Design: Computerization of design procedures, development of computer programs & performance predictions, optimization techniques & their application to design problems.

NOTE: The question paper shall have eight questions in all organized into four sections, each section having two questions from each of the four units. The candidate shall have to attempt five questions in all, selecting at least one question from each unit.

TEXT BOOKS:

1. M.G.Say, Performance and design of ac machines, CBS Publishers.
2. S.K. Sen., Principles of electrical machine design with computer programs, Oxford and IBH publishing co.

1987.

3. A.E.Clayton, Hencock: Performance and design of dc machines, CBS Publishers.

REFERENCE BOOKS:

1. J.H. Kuhlmann, Design of electrical operators, John Willey, 1957.

2. CG Veinott, Theory and design of small induction machines, MGH, 1959.

3. A Shanmugasundarem, Electrical machine design databook.

Electrical Machine Design

SOLVED QUESTION PAPER-1

Note: Attempt *Five* questions in all, selecting one question from each unit. All question carry equal marks.

UNIT-I

Q. 1: Find an expression to find the maximum value of permissible core length. What is the limiting value of armature diameter?

Sol: In the DC machines, whenever possible, single turn coils are used for lap windings, as a simplex wave winding is preferred to a lap winding with multi-turn coils. The number of turns per coil and the number of coils are so chosen that the voltage between adjacent commutator segments is limited to a value where there is no possibility of a flashover. Normally, the maximum voltage between adjacent segments at load should not exceed 30V.

Average voltage between adjacent segments at no load,

E_c = no. of conductors between adjacent segments x voltage per conductor at no load

= 2 x turns between adjacent conductors x average voltage per conductor at no load = 2 x turns per coil x no. of coils between adjacent segments x average voltage per

conductor at no load

$$\mathbf{E_c = 2 . T_c . N_c . e_c}$$

where T_c = turns per coil

N_c = coils connected between adjacent segments

= p/2 or 1 for wave or lap windings respectively

e_c = average voltage per conductor at no load.

$$\mathbf{e_c = B_{av} . L . V_a}$$

So, the average voltage between adjacent segments at no load is

$$\mathbf{E_c = 2 . T_c . N_c . B_{av} . L . V_a}$$

Maximum voltage between adjacent segments at load,

$$\mathbf{E_{cm} = 2\, T_c . N_C . B_{gm} . L . V_a}$$

$\mathbf{E_{cm} = 2 . T_c . B_{gm} . L . V_a}$ **for Lap winding**

& $\mathbf{E_{cm} = p . T_c . B_{gm} . L . V_a}$ **for Wave winding**

Now, $B_{gm} = 1.3\, B_g$ (Usually)

So, $E_{cm} = 2\, T_c\, N_c\, 1.3 B_g\, L\, V_a$

$= 2 . T_c . N_c (1.3\, B_{av}/K_f) . L . V_a$

Take $K_f = 0.66$

$E_{cm} = 2 T_c N_c\, 1.3\, (B_{av}/0.66)\, L\, V_a$

$= 4 . T_c . N_c . B_{av} . L . V_a$

$E_{cm} = 4 . T_c . N_c . e_z$

So, $\mathbf{e_z = E_{cm} / (4 . T_c . N_c)}$

As the max. value of voltage between commutator segments at load E_{cm}, should not exceed 30V.

Thus, avg. value of voltage per conductor at no load > $7.5 / T_c N_c$

Limiting value of Core Length: As the voltage per conductor at no load, $e_c = B_{av} . L . V_a$

& for limiting case, $B_{av} . L . V_a = 7.5 / T_c N_c$

or maximum value of core length is,

$$L = 7.5 / (B_{av} . V_a . T_c . N_c)$$

where, B_{av} = avg. flux density, Wb/m^2

V_a = peripheral speed of armature, m/sec.

T_c = Turns per coil

N_c = no. of coils between adjacent segments of commutator in dc machine

For a simplex lap winding with single layer coils, Take, N_c = 1 and T_c = 1.

So, maximum permissible conductor emf at no load = e_z = 7.5V

& **maximum permissible core length, $L = 7.5 (B_{av} . V_a)$**

For normal designs, $B_{av} = 0.7 Wb/m^2$ and V_a = 30 m/sec

maximum permissible core length, L = 0.36m (approximately)

Limiting value of armature diameter: As the power delivered by the dc machine is,

Output power, $P = E \times I_a \times 10^{-3}$

We have,

E = Total emf per conductor x no. of conductors per parallel paths

$E = e_z . Z / a$

So, $P = (e_z . Z / a) \times I_a \times 10^{-3}$

$= e_z \times (I_a / a) \times Z \times 10^{-3}$

$P = e_z . \pi . D . ac \times 10^{-3}$

Thus, **armature diameter, $D = P \times 10^3 / (\pi . ac . e_z)$**

where, ac = ampere conductors per meter.

ac = 40,000 for limiting values

e_z = 7.5V

π = 3.1457

Thus, maximum permissible armature diameter, D = 0.001 P.

So, for 1000kW dc machine, we have a diameter not less than 0.001 x 1000 = 1meter.

Q. 2: What is the effect of size and ventilation in the design of machine? Describe the heating and cooling cycle.

Sol: As in the energy conversion process in the electrical machines, there is associated the production of power losses. The losses generate the heat and temperature rise inside the machine. The temperature rise if allowed to increase beyond a permissible limit, depending upon the type of insulation used, will deteriorate the insulation and renders the machine useless. Thus it is necessary to provide ventilation and cooling for the machine, so that the temperature rise at any part of the machine does not go beyond the permissible limit.

The rating and size of the machine consequently depends upon how fast the heat is transferred from the inside the machine and dissipated to the ambient medium. Thus, for increasing the rating of an electrical machine, either insulating material of higher temperature limit is developed and used or new cooling techniques are employed. Very small size machines are cooled by the natural means with not external device like fans, pumps etc. As the size of the machine increases, the losses and thus temperature rise increases faster than the increase in surface area, thus requiring artificial cooling methods. The cooling of electrical machines by means of air streams is called as ventilation of the machine.

Temperature –rise time relation: When an electrical machine is switched on and put up on load, the temperature to start with rises at a rate determined by losses. As the temperature rises, the active parts of the machine and various surfaces start transferring and dissipating the heat. The higher the rise in temperature, greater is the heat dissipation. So with rise in temperature, the rate falls because of increased dissipation making the temperature-rise time curve an exponential in nature.

Assumptions: i) The machine can be considered as a homogenous body developing heat internally at uniform rate.

ii) The rate of heat transfer is proportional to the temperature difference.

Let, Q = Power loss or heat developed in the machine, W or J/sec

G = weight of active parts of the machine, Kg

c_p = specific heat, J/ kg-^{0}C

s = cooling surface, m^2

λ = specific heat dissipation, W/m^2-^{0}C

C= cooling coefficient = 1/λ

θ = temperature rise at any time t, ^{0}C

θ_m = Final steady temperature rise, ^{0}C (under heating condition)

t = time, sec. / hr.

τ_h = Heating time constant, sec. / hr.

θ_c = Final steady temperature rise, ^{0}C (under cooling condition)

τ_c = cooling time constant, sec. /hr.

Machine under Heating (Heating Cycle): Consider a situation in a machine at any time 't' from the start and a specific short time 'dt', a small temperature rise 'dθ' takes place.

So, Heat developed during the small interval = Q dt

Heat stored = weight x sp. heat x temp. difference = $G\, c_p\, d\theta$

& let the temperature of surface raises from θ over the ambient medium, then,

Heat dissipated = sp. heat dissipation x surface area x temp. rise x time = $\lambda\, s\, \theta\, dt$

According to heat balance equation,

Heat produced = heat stored + heat dissipated

or $Q\, dt = G\, c_p\, d\theta + \lambda\, s\, \theta\, dt$

or $(Q - \lambda\, s\, \theta)\, dt = G\, c_p\, d\theta$

or $dt = d\theta / [(Q/G\, c_p) - (\lambda\, s / G\, c_p)]$

On integration, we get

$$\mathbf{t = -(G\, c_p / \lambda\, s) \log_e [(Q/G\, c_p) - (\lambda\, s / G\, c_p)\theta] + k}$$

where, k = constant and can be find from the initial conditions at t=0 sec., $\theta = \theta_i$.

$$\mathbf{k = (G\, c_p / \lambda\, s) \log_e [(Q/G\, c_p) - (\lambda\, s / G\, c_p)\theta_i]}$$

So, time,

$$\mathbf{t = -(G\, c_p / \lambda\, s) \log_e [(Q/G\, c_p) - (\lambda\, s / G\, c_p)\theta] + (G\, c_p / \lambda\, s) \log_e [(Q/G\, c_p) - (\lambda\, s / G\, c_p)\theta_i]}$$

or $\mathbf{t = -(G\,c_p / \lambda s) \log_e [((Q/\lambda s) - \theta)/((Q/\lambda s) - \theta_i)]}$

Now, at $t = \infty$, $\theta = \theta_m$ = Final steady temperature and thus there is no further increase in temperature, i.e. $d\theta = 0$.

Thus, heat production = heat dissipated (or heat stored = $G\,c_p\,d\theta = 0$)

$$Q\,dt = \lambda s \theta_m\,dt$$

or

$$\boldsymbol{\theta_m = Q / \lambda s}$$

So, $t = -(G\,c_p / \lambda s) \log_e [(\theta_m - \theta)/(\theta_m - \theta_i)]$

The term, $G\,c_p / \lambda s$ = heating time constant, τ_h.

So, $t = -\tau_h \times \log_e [(\theta_m - \theta)/(\theta_m - \theta_i)]$

$$[(\theta_m - \theta)/(\theta_m - \theta_i)] = e^{(-t/\tau h)}$$

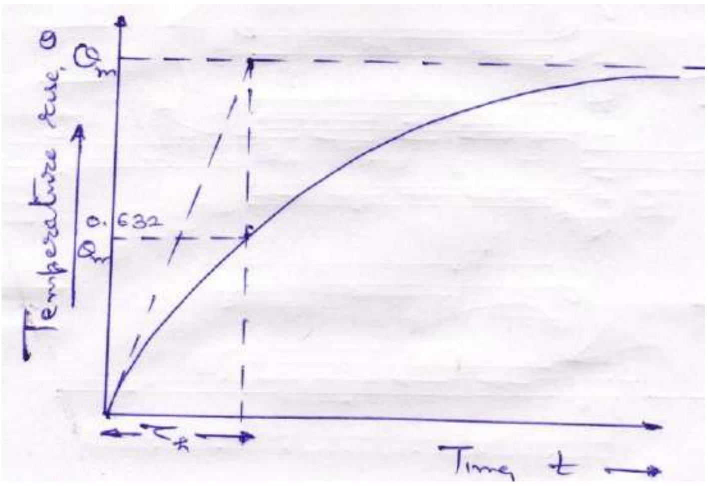
On solving the above equation, we get,

$$\boldsymbol{\Theta = \theta_m \times [1 - e^{(-t/\tau_h)}] + \theta_i \times e^{(-t/\tau_h)}}$$

If the machine starts from the cold conditions, then $\theta_i = 0^0$C and

$$\boldsymbol{\Theta = \theta_m \times [1 - e^{(-t/\tau_h)}]}$$

Thus, temperature-rise time curve is exponential in nature as shown:



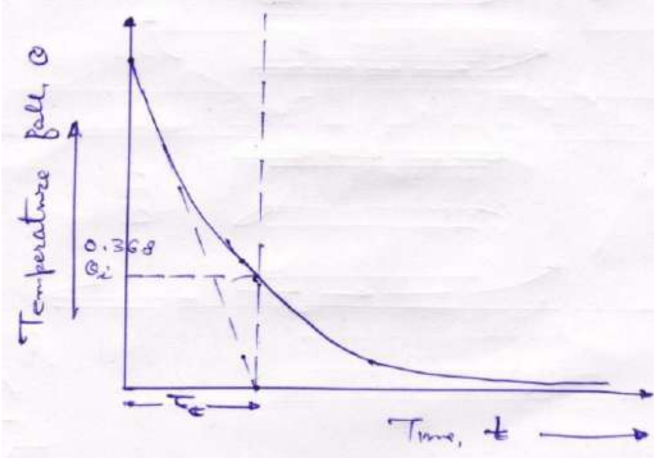
Machine under Cooling (Cooling Cycle): When the load on the machine is lowered thus reducing the generation of losses, or there is a complete shut off of the machine, leading to stoppage of generation of heat, the temperature of machine will fall and temperature rise time curve (-ve) is again exponential in nature.

The equation of this curve can be found by changing the initial condition as

$$\boldsymbol{\Theta = \theta_c \times [1 - e^{(-t/\tau_c)}] + \theta_i \times e^{(-t/\tau_c)}}$$

The value of τ_c will be different from τ_h. Now if the machine is now shut off down, the heat developed is absent, so **final steady temperature rise $\theta_c = 0$.**

Thus, $\boldsymbol{\Theta = \theta_i \times e^{(-t/\tau_c)}}$



UNIT-II

Q. 3: Calculate the approximate overall dimensions of a 200kVA, 6600/400V, 50Hz, 3-phase core type transformer. The following data may be assumed: emf per turn= 10V, maximum flux density = 1.3Wb/m², current density = 2.5 A/mm², window space factor = 0.3, overall height = overall width, stacking factor = 0.9, use a stepped core. For a 3-stepped core, width of largest stamping = 0.9d and net area= 0.6d² where d is diameter of the circumscribing circle.

Sol:

Emf per turn =10V

Emf per turn, $E_t = 4.44 \times f \times B_m \times A_i$

So, $\mathbf{A_i = 0.03465m^2}$

kVA output of 3-phase core type transformer is

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

where, S = kVA output =200kVA

f = frequency = 50Hz

B_m = maximum flux density = 1.3Wb/m²

A_i = net iron area = 0.03465 m²

A_w = window area

δ = Current density = 2.5 A/mm² = 2.5 x 10^{-6} A/m²

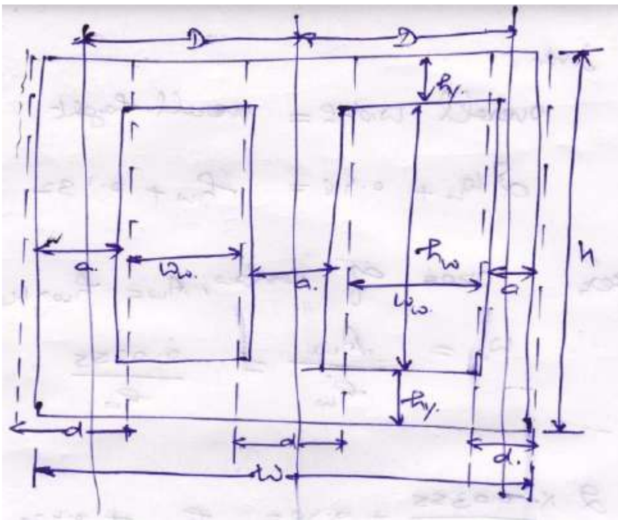
Thus, **window area, $\mathbf{A_w = 0.0355m^2}$**

As the core is 3-stepped core section and

$A_i = 0.6d^2$

or **d = 0.24m.**

Now for a 3-stepped core-type transformer, as shown,



Overall width, $W = 2D + a = 2(W_w + d) + a = 2W_w + 2d + a$

$$W = 2W_w + 2d + 0.9d = 2W_w + 2.9d$$

where, a = width of largest stamping = 0.9d

Thus, in putting the values, $\mathbf{W = 2W_w + 0.48}$

As in the stepped core section, for the yoke,

height of yoke = h_y = a

depth of yoke = d_y = a

So, overall height = $\mathbf{H = h_w + 2h_y = h_w + 2a = h_w + 0.432}$

As given overall height, H = overall width, W

or $h_w + 0.432 = 2W_w + 0.48$

Further area of window, $A_w = h_w \times W_w$

or $W_w = A_w / h_w = 0.0355 / h_w$

On solving the above equation, by putting the value of W_w, we get,

$\mathbf{h_w = 0.2915m.}$

So, the overall width, W = overall height, H

$W = h_w + 0.432 = 0.2915 + 0.432 = 0.7235m$

Thus, **overall width, W = overall height, H = 0.7235m.**

Q. 4: How could you select the air gap length of alternators? Write a brief note on the choice of "shape of pole faces".

Sol:

Length of air gap: The length of air gap influence the performance of a synchronous machine. A large air gap offers a large reluctance to the path of the flux produced by the armature mmf and thus reduces the effect of armature reaction. This results in a small value of synchronous reactance and a high value of short-circuit ratio (SCR). Thus, a machine with a large air gap has,

i) a small value of inherent regulation,

ii) a high value of stability limit,

iii) a higher synchronizing power which makes the machine less sensitive to load variations.

In addition to, a machine designed with a large air gap had better cooling at the gap surface, low teeth pulsation loss, lower noise level and smaller unbalanced magnetic pull. But with the increase in length of air gap, larger value of field mmf is required resulting in increase in the cost of the machine.

a) For Salient pole machines of normal construction and open slots,

Length of air gap / pole pitch = l_g/τ = 0.01 to 0.015

where, l_g = length of air gap at the centre of pole.

b) For turbo-alternators with massive rotors,

Length of air gap / pole pitch = l_g/τ = 0.02 to 0.025

c) For synchronous motors designed with maximum output 1.5 times rated output,

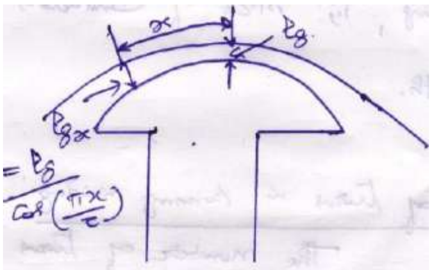
Length of air gap / pole pitch = l_g/τ = 0.02

Shape of Pole Face: The ratio of pole arc to pole pitch, ψ, varies between 0.65 to 0.75.

Ψ = Pole Arc / Pole Pitch = 0.65 to 0.75

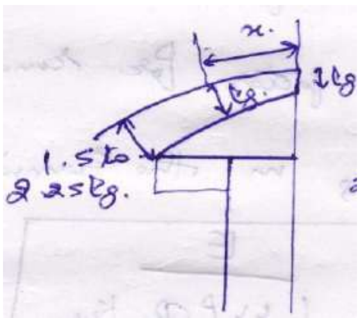
If the value of ψ is too large (ψ> 0.75), the interpole flux linkage becomes excessive leading to the high value of flux density in the pole body and improper flux distribution over the armature and, if the value of ψ is too small a value (ψ< 0.65) will be insufficient overhang of the pole shoe to support the field coil in the radial direction. So, in common practice, ψ is to be taken as 0.7.

In salient pole machines, the length of air gap is not constant over the pole arc, but increase from centre outwards in order to produce the required flux distribution. So in order to make and obtain sinusoidal flux distribution by proper shaping and proportioning the shoe. For an exact sinusoidal flux distribution, length of air gap at a distance x from the centre is,



$$l_{gx} = lg / (\text{Cos}\ (\pi\ x/\tau))$$

A satisfactory air gap flux distribution curve is generally obtained when the pole face is shaped as indicated, where **x = 0.1τ to 0.25τ.**



For machines requiring no damper windings in the pole faces, the tip of the pole face may be rounded off, as shown in full time and for the machines with damper windings, a heavier pole face is generally required, as shown by light line.

UNIT-III

Q. 5: For a single phase induction motor, how would you select i) number of turns in running winding, ii) size of conductors, iii) air gap length.

Sol:

I) Number of turns of running (main) winding: The number of turns of running winding in 1-phase induction motor can be calculated as follows:

Stator induced voltage, $E = 4.44 \, f \Phi_m T_m K_{wm}$

where, T_m = no of turns of running /main winding

K_{wm} = winding factor for running winding

Φ_m = Flux per pole = $B_{av} (\pi D L/p)$

B_{av} = Avg. flux density in Wb/m^2

D = diameter in m.

L = Length of stator, m

P= no. of poles

So, no. of turns in the running winding is,

$$T_m = E/4.44 \, f \, \Phi_m \, K_{wm}$$

The value of stator induced emf E is approx. equal to 95 percent of supply voltage V and the winding factor K_{wm} can be assumed between 0.75 to 0.85. The no. of turns in series per pole for main winding is

$$T_{pm} = T_m / p$$

ii) Running winding conductors:

Current carried by each running winding conductor is, I_m = h.p. x 746/ (V η CosØ).

Thus, area of running winding conductor, $a_m = I_m / \delta_m$.

where, δ_m = Current density for running winding conductor in A/mm^2.

For open type motor split phase, capacitor and repulsion start motor, the current density δ_m can be usually be 3 to 4 A/mm^2. For enclosed motors, much lower values of δ_m should be taken.

iii) Air gap Length: The consideration for making a particular air gap length are same as for 3-phase induction motor, given by empirical formula,

$$\text{Gap length, } l_g = 0.007 \times \text{rotor diameter} / \sqrt{P}$$

a) In order to estimate the length of air gap for small induction motors,

$$l_g = 0.2 + 2\sqrt{(D\,L)} \text{ mm}$$

b) Another expression can be used for small motors is,

$$l_g = 0.125 + 0.35D + L + 0.015V_a \text{ mm}$$

where, V_a = peripheral speed in m/sec.

D = diameter, in m

L = Length of stator bore, in m.

Q. 6: Find the main dimensions of a 15kW, 3-phase, 400V, 50Hz, 2810 rpm squirrel cage induction motor having an efficiency of 0.88 and a full load power factor of 0.9. Assume specific magnetic loading = 0.5Wb/m^2, specific electric

loading = 25000A/m, rotor peripheral synchronous speed = 20 m/sec.

Sol:

Given, kVA, Q = kW/ (CosØ x η) = 18.94kVA

Output coefficient, C_o= 11 K_w B_{av} ac x 10^{-3}

Given, B_{av} = sp. magnetic loading = 0.5Wb/m^2

ac = sp. electric loading = 25000A/m

Take, K_w = winding factor = 0.955

Thus, C_o = 131.3

The speed of rotor at full load is 2810rpm and the nearest synchronous speed (N_s) corresponding to 50Hz is 3000rpm.

Thus, synchronous speed, n_s = 3000 / 60 = 50 r.p.sec.

So, **product (volume), D^2 L = Q / (C_o n_s) = 2.88 x 10^{-3} m^3**

As the rotor peripheral speed = 20 m/sec

or $\pi D n_s = 20$

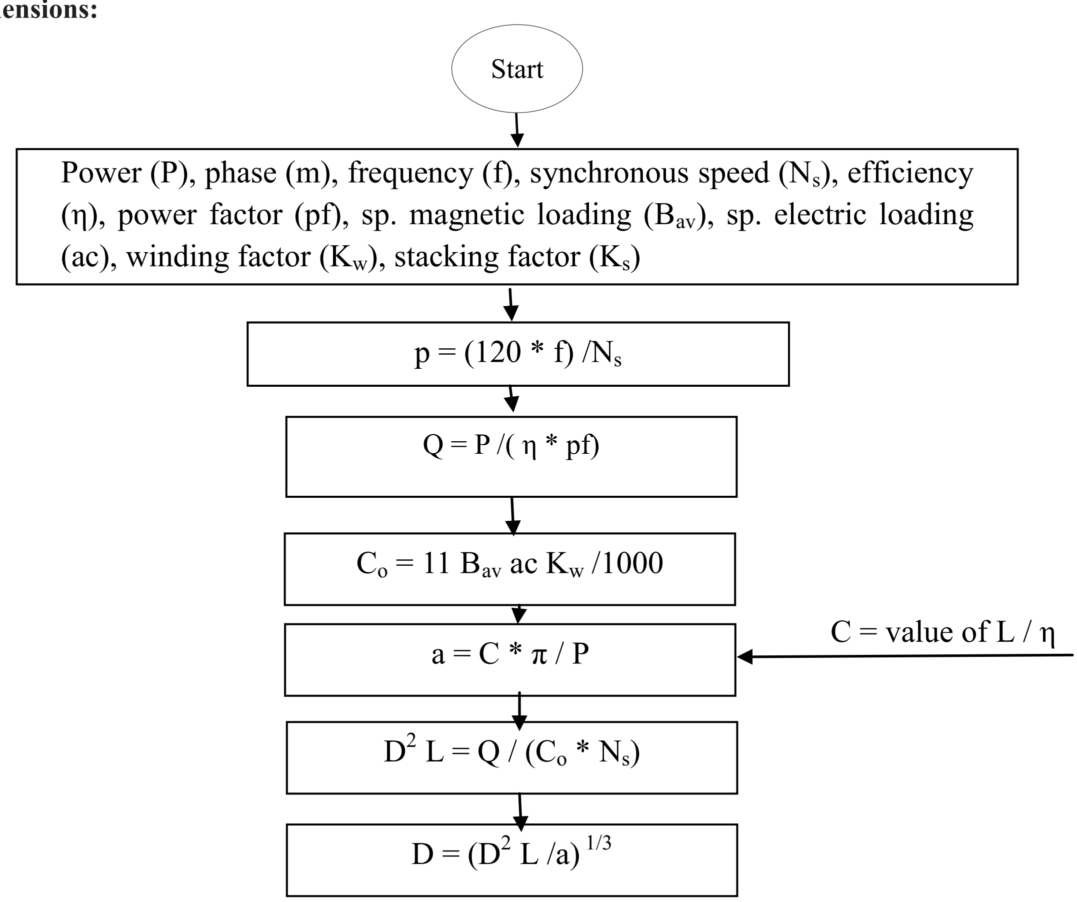
So, **D = 0.1275 m.** and **L = 0.177m**

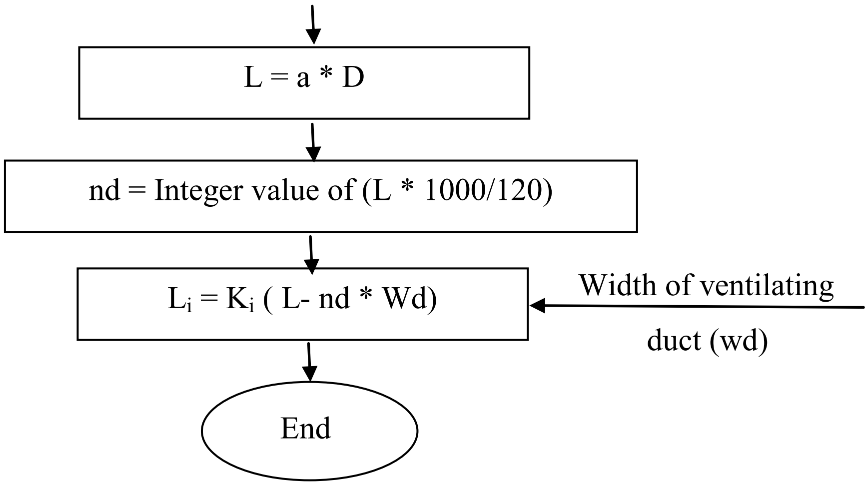
UNIT-IV

Q. 7: Draw and describe the flow chart of designing of main dimensions of an induction motor and its stator design.

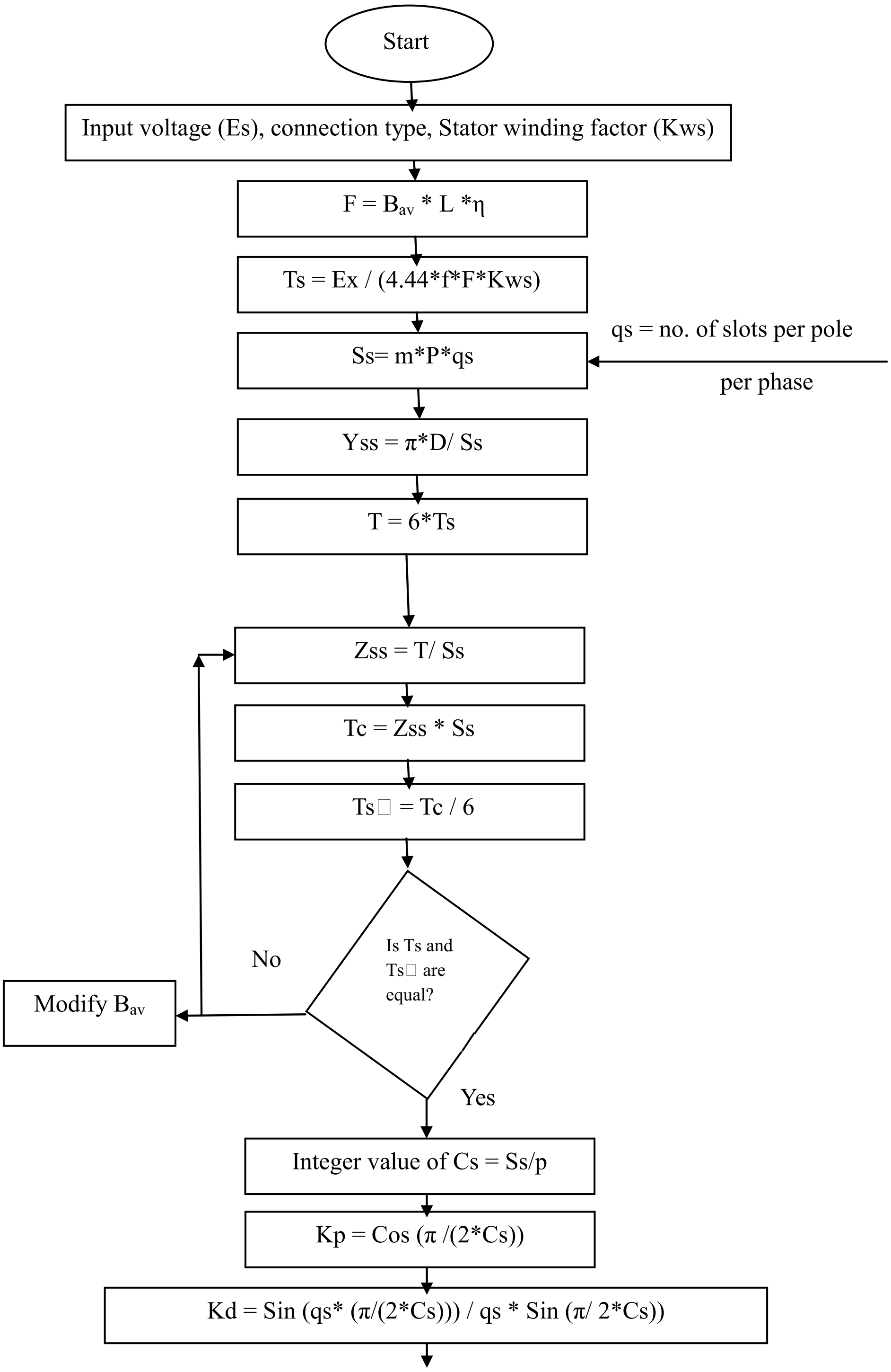
Sol: The flow charts of main dimensions designing and its stator design is as under of the induction motor.

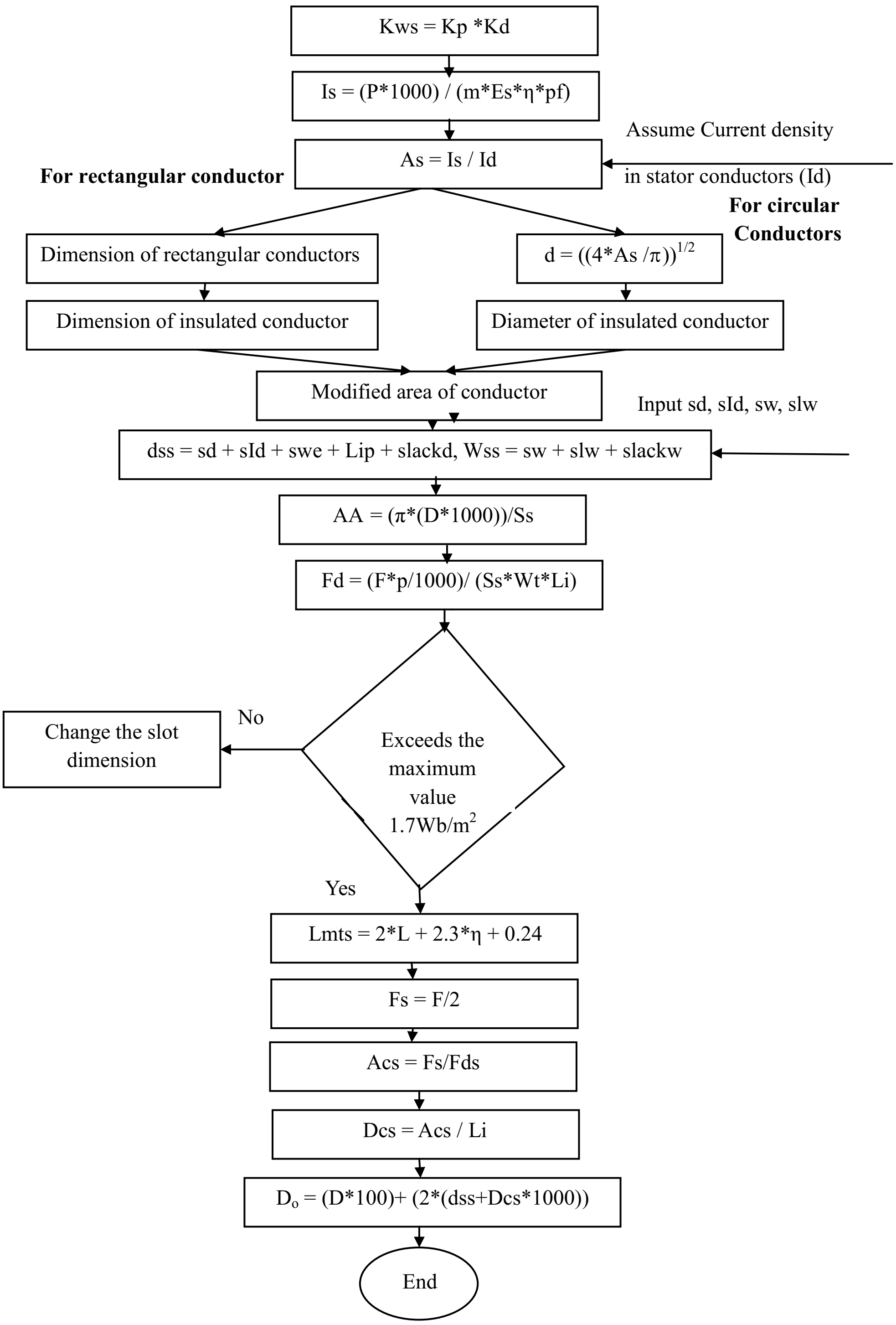
Main Dimensions:





Stator Design:





where, sd = no. of conductor in depth.

sId = insulation along depth of the conductor.

sw = no. of conductor in width

sIw = insulation along width of the conductor.

Q. 8: Write an algorithm for the design of the main dimensions of DC motor. Write the program for it any language.

Sol: Algorithm for design of main dimensions of DC motor with programming code in C language:

```
# include <stdio.h>
# include (conio.h>
# include <math.h>
# define pi 3.141592654
# define mho (0.000001257)
int main (void)
{Clrscr ();
/*Main dimensions*/
Clrscr();
float P, n,eta, Bav, ac, Ki, p, Pa, Co, product, shi, Val, D;
float L, tow, b, Va, Y, nd, Li, f, t;
FILE *fp;
fp= f open (“C:\\dem.txt”, “W');
printf (“enter the power of the motor (kW):       ”);
scanf (“%f”, &P);
fprintf (fp, “\n The power of the motor (kW): “       ,P);
printf (“enter the synchronous speed of the machine (RPM):     ”);
scanf (“%f”, &n);
fprintf (fp, “\n The synchronous speed of the motor is %f(RPM):“      ,n);
printf (“enter the efficiency of the motor:      ”);
scanf (“%f”, &eta);
fprintf (fp, “\n The efficiency of the motor power of the motor is %f:“      ,eta);
printf (“enter the value of magnetic loading (Wb/m^2):      ”);
scanf (“%f”, &Bav);
fprintf (fp, “\n The magnetic loading of the motor is %f (Wb/m^2):“     ,Bav);
printf (“enter the value of electric loading (A/m):      ”);
scanf (“%f”, &ac);
fprintf (fp, “\n The magnetic loading of the motor is %f (A/m):“    ,ac);
printf (“enter the value of stacking factor:       ”);
scanf (“%f”, &Ki);
fprintf (fp, “\n The value of stacking factor is %f“     ,Ki);
printf (“enter the no. of poles:       ”);
scanf (“%f”, &p);
fprintf (fp, “\n The no. of poles are %f:“        ,p);
Po = ((1+2*eta)/ (3*eta))*P;
Fprintf (fp, “\n Power developed by the armature is %f W”    , Po);
```

```
Co = (pi * pi* Bav*ac)/1000;
fprintf (fp, "\n output coefficient is %f"   , Co);
product = Pa /(Co*n/60);
fprintf (fp, "\n product D^2L is %f m^3: ", product);
printf ("enter the value of pole arc to pole pitch (0.64 to 0.72):      ");
scanf ("%f", &shi);
shi = 0.67;
fprintf (fp, "\n Ratio of pole arc to pole face is  %f :"   , shi);
Val1= ((product*p)/ (shi*pi));
D = pow (Val1, .333);
fprintf (fp, "\n calculated diameter of armature is %f m", D);
printf ("The calculated diameter is %f m:      ",D);
printf (" Enter the standard diameter(m):    ",D);
scanf ("%f", &D);
fprintf (fp, "\n the standard diameter of armature is %f m", D);
L = product / (D*D);
fprintf (fp, "\n calculated length of armature is %f m", L);
printf ("The calculated length of core is %f m:      ",L);
printf (" Enter the standard core length (m):    ",L);
scanf ("%f", &L);
fprintf (fp, "\n the standard length of armature core is %f m", L);
tow = (pi*D)/p;
fprintf (fp, "\n pole pitch is %f m", tow);
b = shi * tow;
fprintf (fp, "\n pole arc is %f m", b);
Va = (pi*D*n)/60;
fprintf (fp, "\n the peripheral speed  is %f m/sec", Va);
printf ("\n core length is %f m:      ",L);
printf ("\n consider the length of one ventilating duct is 0.13m");
fprintf (fp, "\n consider the length of one ventilating duct is 0.13m");
printf ("\n consider the width of one ventilating duct (m)"   );
scanf ("%f", &Y);
fprintf (fp, "\n the width of the ventilating duct is %f m", Y);
nd = int (L/0.13);
```

```
fprintf (fp, "\n the no. of ventilating duct is %f", nd);
Li = Ki * (L-nd*Y);
fprintf (fp, "\n the net iron length is %f (m)", Li);
f = (p*n)/ (2*60);
fprintf (fp, "\n Frequency of flux reversal is %f (Hz)", f);
t = 0.35;
fprintf (fp, "\n The thickness of lamination is %f (mm)", t);
```

Electrical Machine Design

SOLVED QUESTION PAPER-2

Note: Attempt *Five* questions in all, selecting one question from each unit. All question carry equal marks.

UNIT-I

Q. 1 a): Discuss various types of enclosures of electrical machines.

b): What is the role of Commutator? Discuss its drawbacks.

c): How loading, poles and speed of DC machines are chosen?

Sol:

a): Types of enclosures: The scheme of ventilation is closely related to the type of motor enclosures. The various types of enclosures as per Indian Standards are:

i) Open Type: There is no protection of any type and no restriction to ventilation. The examples of this type are:

1) Open pedestal (OP).

2) Open-end bracket (OEB).

ii) Protected Type: The example of this type is screen-protected machine (SP), the protection may be screen or by fine-mesh covers.

iii) Drip, splash and hose-proof type: Protected type machines where the end shield, ventilation openings are designed to exclude filling water or dirt, vertically, at any angle between the vertical and 100^0 from it and jets of water/liquid.

i) Ventilated type: The end shields are closed type except for flanged apertures for connection to pipes along with the cooling air is drawn in or let out, such as pipe ventilated (PV) or Duct ventilated (DVD).

ii) Totally enclosed type: These are protected by enclosures without openings but are not necessarily air tight. The examples of this type are:

1). Totally enclosed type, naturally cooled (TE).

2). Totally enclosed type, fan cooled (TEFC).

3). Totally enclosed type, separately air cooled (TESAC).

4). Totally enclosed type, water cooled (TEWC).

5). Totally enclosed type, closed air circuit machine.

6). Totally enclosed type, closed gas circuit machine.

vi) Special enclosures: A machine so constructed that it can work in the given atmosphere/ situation without further protection, such as, 1). Weather-proof (WP).

2). Water-tight (WT).

3). Submersible machine.

4). Flame Proof machine.

b): Commutator in DC machines: The function of the commutator in dc machine is to rectify the alternating current induced in the armature conductors in dc machine. It is cylindrically shaped and is placed at one end of the armature. The essentials of the construction are a number of copper bars or segments or coils separated from one another by a suitable insulating material and connected to the armature conductors. The connection of armature conductors to the commutator is made with the help of risers. The riser connecting the segments to the armature coils are made of copper strips for large machines. The outer end of the rise is shaped so as to form a clip into which the armature conductors are soldered.

Satisfactory operation and performance of a dc machine is dependent under good mechanical stability of the commutator under all conditions of speed and the temperature with the operating range. Mechanically unstable commutator manifests itself in a poor commutation performance and results in unsatisfactory brush life as well as necessitating frequent machining of commutator to restore the surface.

Drawbacks of Commutator: Commutator in dc machine or commutation in dc machine is always a serious problem to the designers of DC machines because good commutation depends on many factors.

It is important that the temperature of the contact surface is high enough to initiate the chemical process. The temperature primarily depends upon the current density in the brush, the frictional losses and the air cooling mechanism. Second important factor is the humidity of the surroundings air, because the moisture is the most important essential element in the chemical process.

a) **Sparking**: The sparking is never desirable for any machine operation. The most probable common reason for sparking is improper contact between the brush and the surface of the commutator.

b) **Poor brush contact**: The poor brush contact at the commutator leads to severe damage to the commutator surface.

c) **Vibrations**: Vibrations affect the brush contact adversely. Vibrations may be produced due to unbalanced coupling fans, improper and poor alignment, causes the commutation.

c):

i) Specific magnetic and electric loading: The output power of a dc machine is proportional to the product of their specific magnetic and electric loadings as P α (B_{av} x ac). For a particular machine output, the values of specific magnetic and electric loadings are interdependent, i.e., if value of one is chosen higher, the value of other has to be assumed lower.

The specific magnetic loading is limited by the saturation in the magnetic circuit. The air gap density, B_{av}, can be increased, only if sufficient area is available in the magnetic circuit. The product of B_{av} x ac is a major factor and the increase of one at the expense of other may not lead to increase in the rating. In fact, the values of specific loadings should be so chosen that the optimized design of dc machine is obtained.

ii) Selection of number of poles: The value of the output coefficient C_o can be obtained after suitable choice of values of B_{av} and ac and then the value of power output is obtained.

Output power developed by the armature, $P_a = C_o. D^2.L.n$

& output coefficient, $C_o = \pi^2. B_{av}. ac. 10^{-3}$

It now remain to select appropriate values of D and L which corresponds to the calculated value of D^2L. In order to obtain suitable proportions for the machine, it is necessary to consider both the magnetic as well as electric loadings. So far as, the magnetic circuit is concerned, it is necessary to choose suitable number of poles and also to suitably proportion them. The number of poles used in a dc machine has an important bearing upon both the magnetic and electric circuits. For the choice of poles, let the length, diameter of machine, the specific magnetic and electric loadings are fixed and number of poles can be varied as:

Φ_T = Total flux around the air gap = p Φ = B_{av} x π D L.

& AC= Total ampere conductors over the armature periphery = I_z x Z = (I_a /a) Z = ac. π. D

are both constant.

iii) Speed: Speed/ frequency of the flux reversal in dc machine is given by, f = p. n/2.

So, if we chose a large no. of poles, the frequency is high. The frequency of alternations of magnetic flux in dc machines should not be very high as it would give rise to excessive iron losses in the armature core. Generally, the value of frequency f lies between 25-50Hz, but may be more in small machine, typically high speed series motor designed with a low air gap density.

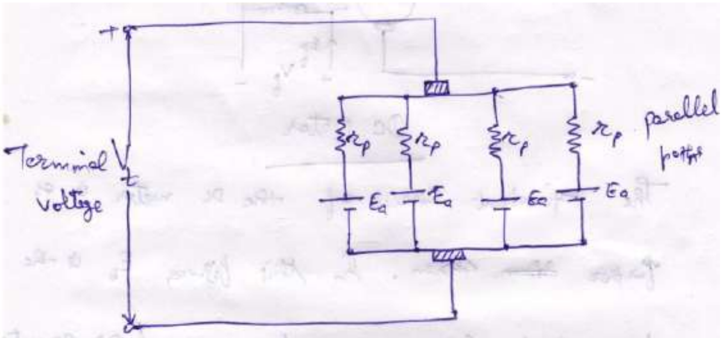
Q. 2: Write technical note on the following:-

a): Electrical equivalent for a separately excited DC motor.

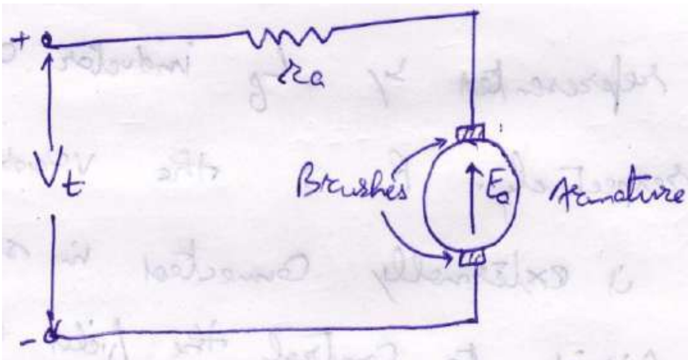
b): Conductor design and winding selection criteria of DC machine.

Sol:

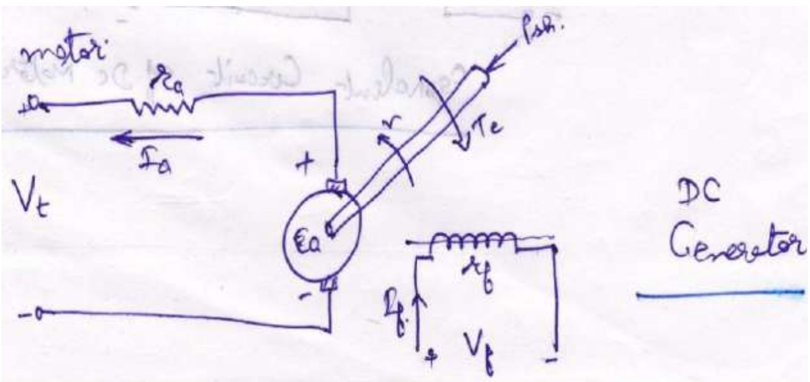
a) Circuit model of DC machine: In dc machines, all parallel paths in the armature are symmetrical. Each path has a generated emf E_a and a resistance r_P as indicated in fig. where, for the sake of simplicity, four parallel paths are shown.

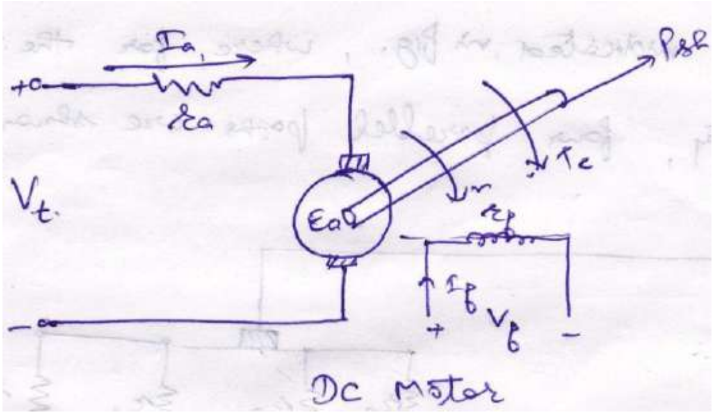


Viewing form machine terminals, the armature circuit can be replaced by circuit model, where series resistance r_a = r_P/ a and 'a' is the number of parallel paths.

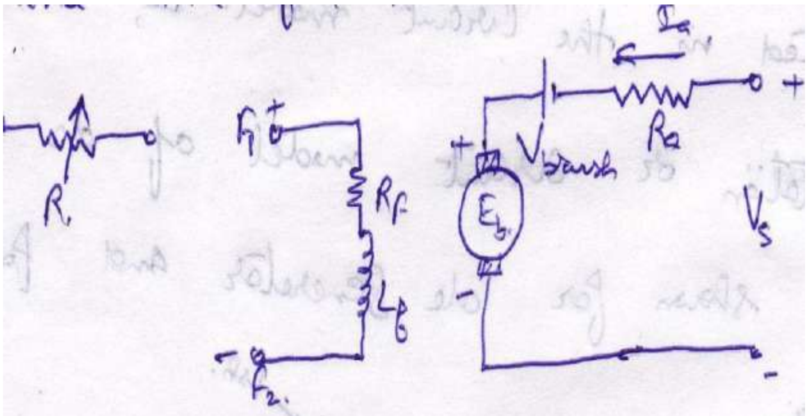


The field winding of a dc machine must also be represented in the circuit model. So, the schematic representation or circuit model of dc machines is as shown for dc generator and dc motor.



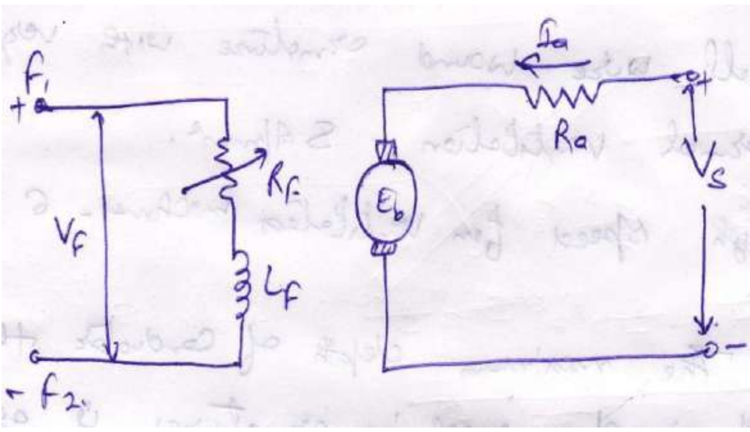


The equivalent circuit of the dc machine is as further shown. In this figure, E_b is the back emf (E_g is the generated emf in dc generator) in the armature and it is shown as ideal source, R_a is the armature resistance and V_{brush} is the brush contact voltage drop. The field coils which produce the main flux in motor are represented by inductor L_g and resistance R_F respectively. R is the variable resistance which is externally connected in series with the field circuit to control the field current and hence the flux produced by the field.



Equivalent circuit of DC motor

The simplified equivalent circuit of a dc motor, when R_F is the combination of R and the field resistance is as shown.



a) Conductor design/ Cross-section of armature conductors: As the armature current in dc machine,

$$I_a = (P_a / E) \times 10^3$$

& the armature current may be calculated from

$$I_a = I_L + I_f \qquad \text{for dc generator}$$

$$I_a = I_L - I_f \qquad \text{for dc motor}$$

where, I_L = Line Current and I_f = Field current.

So area of the each armature conductor is,

$$\mathbf{a_2 = I_2 / \delta_a = I_a / \delta_a \ mm^2}$$

where, δ_a = Current density of the armature conductors, A/ mm^2.

The current density in the armature conductors should be taken as high as efficiency and temperature rise conditions permit. This is because a large value of δ_a reduces the size of conductors and thus there is a saving in the cost of copper. Also the slot area of the armature core becomes small and thus shallow slots can be employed. The following values of current density δ_a may be used:-

i) Large strap wound armatures with very good normal ventilation = 4.5A/mm^2.

ii) Small wire wound armature with very good normal ventilation = 5 A/mm^2

iii) High speed for ventilated machine = 6 to 7 A/mm^2

The maximum depth of conductor that can be used in dc machine armature is about 19mm where frequency is 25Hz. In case where the frequency is relatively high, the conductor depth should not be exceeding 15mm. In further case, the depth increases the above limits as with the high speed machines, it is necessary to laminate the conductors.

Choice of armature winding: The armature winding of a dc machine is defined as an arrangement of conductors designed to produce emf's by relative motion in a hetropolar magnetic field. Electrical machines employ groups of conductors distributed in slots over the periphery of the armature core. The groups of conductors are connected in various types of series-parallel combinations to form armature winding.

In dc machines, simplex windings are used in preference to multiplex wave windings owing to the laminations imposed by equalizer connections in the multiplex windings. The choice usually lies simplex lab and wave windings.

UNIT-II

Q. 3: A 800kVA, 11/0.4kV, 3-phase, delta/star transformer has ohmic losses of 3kW on high voltage side and 2kW on low voltage side under rated load. The total leakage reactance is 0.08p.u. Find the ohmic values of equivalent resistance and reactance on both star and delta sides.

Sol:

Simplex Lap Winding	Simplex Wave Winding
1. Number of parallel paths of windings is equal to number of poles. So the current is each path = (1/p) times full load current. Each parallel path will develop an emf = E.	1. Number of parallel paths = 2. Current is each path = half of full load current. Each of the two parallel paths will develop an emf = E.
2. Total number of conductors are large compared to wave winding and current per path is less. So, reduced conductor cross-sectional area is required. But the total volume of copper used may be same in both the cases.	2. Total number of conductors are less and current path is high. So, large cross-section area is required.
3. Equalizer connections have to be used making the machine costly.	3. No equalizer connections are required. Hence, reduces the cost of the manufacturing and repairs
4. Normally not used for small machines, beyond current ratings of 400A limit.	4. Used for small machines, used upto the current rating of 400A.

UNIT-II

Q. 3: A 800kVA, 11/0.4kV, 3-phase, delta/star transformer has ohmic losses of 3kW on high voltage side and 2kW on low voltage side under rated load. The total leakage reactance is 0.08p.u. Find the ohmic values of equivalent

resistance and reactance on both star and delta sides.

Sol:

Given, kVA= 800kVA, 1^0 Line voltage= 11kV, 2^0 Line voltage= 400V

1^0 ohmic (copper losses) = $I_1^2R_1$ = 3kW,

2^0 ohmic (copper losses) = $I_2^2R_2$ = 2kW

Total leakage reactance X = 0.08p.u.

Transformation ratio, $K = V_2/V_1 = 0.021$

On H.V. side:

Total ohmic losses = 3 + 2 = 5kW

Full Load current = 800 / (3 x 11) = 24.24A

Equivalent resistance in ohms,

$\mathbf{r_{e1} = kW \times (kV)^2 / (kVA)^2 = 5000 \times (3 \times 11)^2 / (800)^2 = 8.508\Omega}$

For delta connected impedance, it is required that,

$Z\,(p.u.) = (Z/3 \text{ in } \Omega)\,(MVA)_B / (kV)_B^2$

So, equivalent resistance in p.u. $= (8.508 / 3) \times (0.8/ 11^2) = 0.01875$ p.u.

Thus,

Equivalent reactance in Ω, $X_{e1} = X_e\,(p.u.) \times 3 \times (kV_B)^2 / (MVA_B)$

or,

$\mathbf{X_{e1} = 3 \times (0.08)\,(11^2) / 0.8 = 36.3\Omega}$

On L.V. side:

Total ohmic losses = 3 + 2 = 5kW

Full Load current = $800 \times \sqrt{3} / (3 \times 0.4) = 1154.7$A

Equivalent resistance in ohms,

$\mathbf{r_{e2} = kW \times (kV)^2 / (kVA)^2 = 5000 / (1154.7)^2 = 0.00375\Omega}$

For star connected impedance, it is required that,

$Z\,(p.u.) = (Z \text{ in } \Omega)\,(MVA)_B / (kV)_B^2$

So, **equivalent resistance in p.u.** $\mathbf{= (0.00375) \times (0.8/ 0.4^2) = 0.01875}$ **p.u.**

Thus,

Equivalent reactance in Ω, $X_{e1} = X_e\,(p.u.) \times (kV_B)^2 / (MVA_B)$

or,

$\mathbf{X_{e1} = (0.08)\,(11^2) / 0.8 = 12.1\Omega}$

Q. 4 a): Explain principle of operation and operational performance of synchronous machines. Mention their ratings and general dimensions.

b): Obtain equivalent circuit of a single-phase transformer. Derive various circuit parameters. Discuss various

losses in a transformer and its efficiency.

Sol:

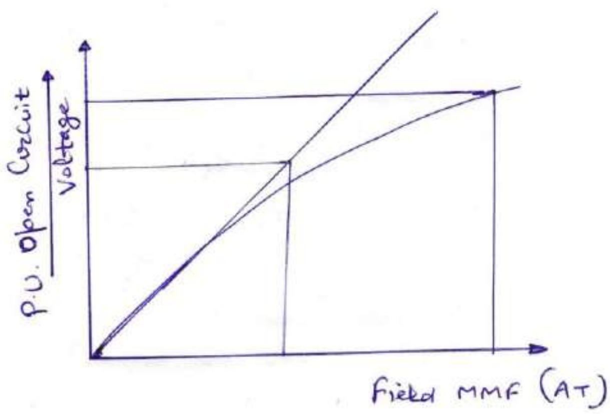
a): Principle of operation of Synchronous Machine: Synchronous machines or AC machines operate on the same fundamental principle of electromagnetic induction as dc machines. They also consist of an armature winding and a magnetic field. But there is one important difference between the two. Whereas in dc machines, the armature rotates and the field system is stationary, the arrangement in synchronous machine is just the reverse of it. In this case, standard construction consists of armature winding mounted on a stationary element called stator and the field winding on a rotating element called rotor.

The stator consists of a cast iron frame, which supports the armature core having slots, on its inner periphery for housing the armature conductors. The rotor is like a flywheel having alternate N and S poles fixed on its outer rim. The magnetic poles are excited/ magnetized from a dc supplied by a dc source at 125V to 600V. In most cases, necessary exciting/ magnetizing current is obtained from a small d.c. shunt generator. Because the field magnets are rotating, this current is supplied through slip rings and the slip rings & brush gear are of light construction due to low dc voltage. However, brushless dc excitation can be used, consists of 3-phase ac exciter and a group of rectifiers supply dc to the synchronous machine.

When rotor rotates, the stator conductors being stationary, cut the rotating magnetic field and hence have induced emf produced in them. Because the magnetic poles N and S are alternate, they induce an emf and current in armature conductors, first flows in one direction and then in other direction. Hence, an alternating emf is produced in the stator armature conductors, whose frequency f depends on the number of N and S poles moving past a conductor in one second.

Operational performance of Synchronous Machine: The various operational performance of synchronous machines is as under:-

I) Open Circuit characteristics: The open-circuit characteristics give the relation between the terminal voltage at no load and the corresponding field mmf per pole.



ii) Full Load Field MMF: The values of full load field mmf AT_{FL} can be calculated as follows:

Field mmf equivalent to armature mmf per pole = $(2.7\, T_{ph}\, I_{ph}\, K_w) \times \rho_i / p$

where, I_{ph} = current per phase

T_{ph} = No. of turns per phase

K_w = Winding factor

p = no. of poles.

iii) Short Circuit characteristics: The relationship between the field mmf and the armature current when the armature is short-circuited is known as the short-circuit characteristics (S.C.C.). The armature short-circuit current is proportional to the field mmf over a wide range and so the S.C.C. is a straight line.

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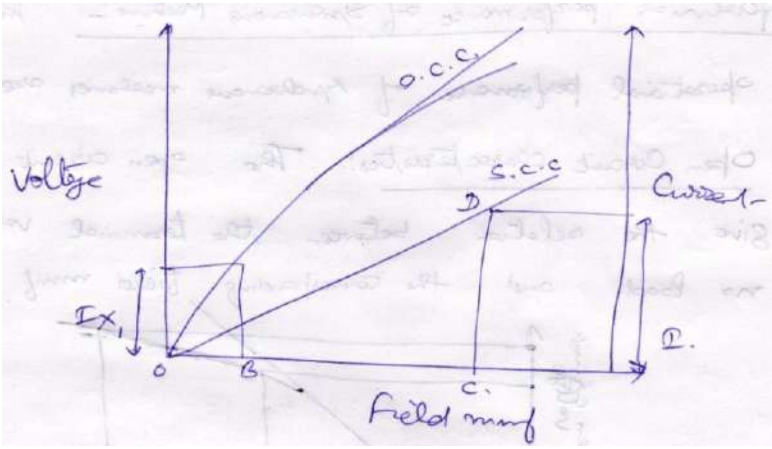
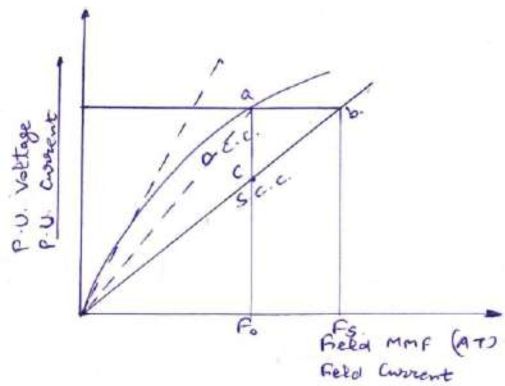


From the short-circuit condition, the armature current is practically in quadrature with the voltage and thus the armature mmf has a demagnetising effect on the field. The voltage induced in the armature when short-circuited is nearly equal to IX, the leakage reactance drop. The field mmf equivalent to armature mmf = $\rho_d \times AT_a$.

I) Short-Circuit Ratio (SCR): The short-circuit ratio (SCR) of a synchronous machine is defined as the ration of field current required to produce rated voltage on open-circuited to field current required to circulate the rate current at short-circuit.

$$\textbf{SCR} = \frac{\textbf{Field current for rated voltage at O.C.C.}}{\textbf{Field Current for rated current at S.C.C.}}$$



$SCR = OF_o / OF_s = c\,F_o / b\,F_s = c\,F_o / a\,F_s = 1/(a\,F_s / c\,F_o)$

or, **SCR = 1/ (per unit voltage on open circuit / per unit current on short circuit)**

or, **$SCR = 1/X_d$**

Thus, the short-circuit ratio (SCR) is the reciprocal of synchronous reactance, X_d. For modern turbo-alternators, the SCR is normally between 0.5 to 0.7. For salient pole hydroelectric generators, SCR varies from 1.0 to 1.5.

Ratings of Synchronous Machines: The starting point of a design of a synchronous machine is the specifications/ ratings to which the machine must be built. The man specifications are: kVA capacity/ kW capacity, voltage rating, speed, number of phases, frequency, regulation, efficiency, temperature rise, cooling methods, type of prime-move, excitation, excitation voltage and current, transportation to site etc.

All these information are necessary for the designer.

General dimensions: The output equation of a 3-phase synchronous machine is given as under:-

$$\mathbf{kVA = C_o D^2 L n}$$

where, $\mathbf{C_o = output\ coefficient = 1.11\, \pi^2 K_w B_{av}\, ac \times 10^3}$

D = diameter of armature/stator bore, m

L = length of stator bore, m

n = peripheral speed, r.p.s.

The output equation can be worked out in terms of peripheral speed.

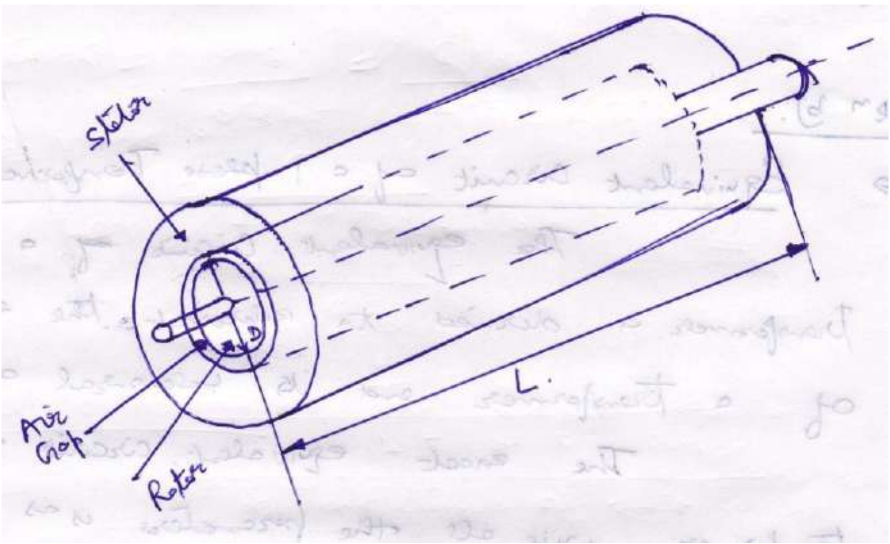
Peripheral speed, $\mathbf{v = \pi D n}$

So, $D = v/(\pi n)$

Put this in kVA equation, we get,

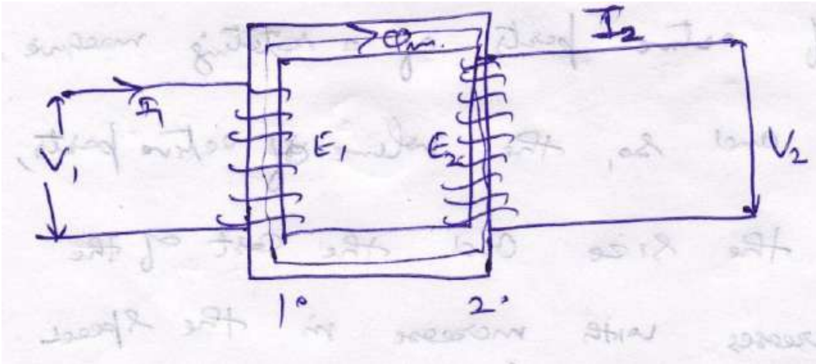
$$\mathbf{kVA = 1.11 K_w B_{av}\, ac \times 10^3 (v^2/n) L}$$

The armature diameter D and the armature core length L are known as the main dimensions of a synchronous machine.

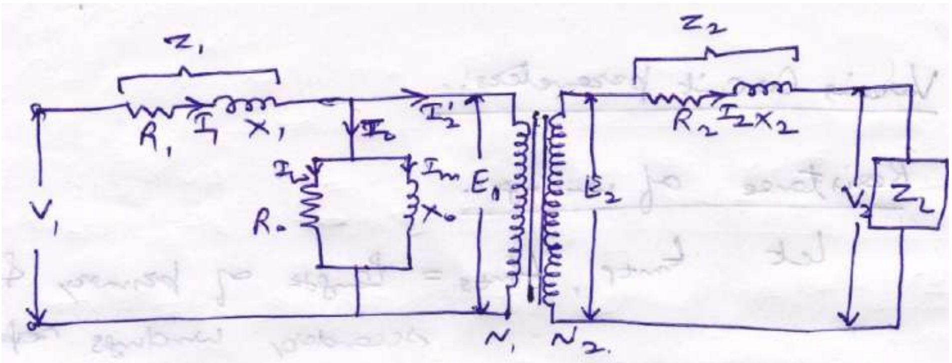


For the output equation, it is observed that the product $D^2 L$ will decrease with increase in speed and/or increase in output coefficient. The volume of active parts of a rotating machine is $(\pi/4)\, D^2 L$ and so, the volume of active parts and hence the size and the cost of the machine decreases with the increase in speed and/or increase in the value of output coefficient. From the equation of output coefficient, the output coefficient is proportional to the product of specific magnetic loading (B_{av}) and specific electric loading (ac), so the size and hence of cost of machine decreases, if increased values of B_{av} and ac are used.

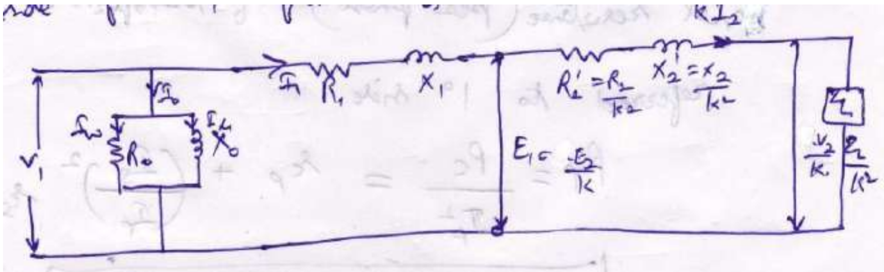
a) Equivalent circuit of 1-phase Transformer: The equivalent circuit of a 1-phase transformer is desired to represent the each component of a transformer and its behavioural aspects. The exact equivalent circuit of a practical transformer with all the parameters is as shown, in which the resistance and leakage reactance of the transformer are imagined to be external to the winding whose only function is to transform the voltages.



The no-load current I_o is simulated by pure inductance X_o taking the magnetizing current I_m/ I_μ and a non-inductive resistance R_o taking the working component I_w in parallel across the primary circuit. The values of $X_o = E_1/ I_\mu$ and or $R_o = E_1 / I_w$ and the values of E_1 is obtained by subtracting vertically I_1Z_1= from V_1.



To make transformer calculations simpler, it is preferable to transfer the voltage, current and the impedance either to the primary or to the secondary sides. So, it becomes more convenient to work on one winding only. The exact equivalent circuit referred to primary side of a transformer is:



Exact equivalent circuit of 1-phase Transformer referred to 1^0 side

Various Circuit parameters:

a) Resistance of winding:

Let L_{mtp}, L_{mts} = length of primary and secondary windings respectively, m

r_p , r_s = resistance of primary and secondary windings respectively, Ω

So, $$r_p = \rho (T_p .L_{mtp}) / a_p$$

& $$r_s = \rho (T_s .L_{mts}) / a_s$$

where, T_p = no. of turns of 1^0 winding

T_s = no. of turns of 2^0 winding

a_p = area of 1^0 winding, m^2

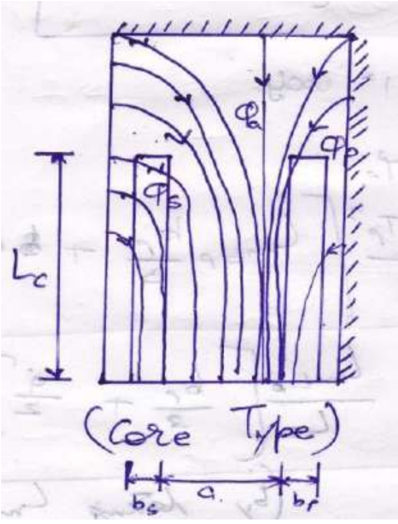
a_s = area of 2^0 winding, m^2

ρ = electrical resistivity of winding material used, Ω-m.

Total $I^2 R$ losses in windings, $P_c = I_p^2\, r_p + I_s^2\, r_s$ $R_p = r_p + (T_s/T_p)^2\, r_s$ Total resistance (per phase) of transformer referred to 1^0 side, $R_p = P_c / I_p^2 = r_p + (I_s/I_p)^2\, r_s$

$$R_p = r_p + (T_s/T_p)^2\, r_s$$

b) Leakage Reactance of Winding: The estimation of leakage reactance is primarily the estimation of the distribution of leakage flux and the resulting flux leakages of the primary and secondary windings. The distribution of leakage flux depends upon the geometrical configuration of the coils and neighbouring iron masses and also on the permeability of the latter. The most common arrangements of core and the windings alongwith the distribution of leakage fluxes in the core and the shell type transformers is as shown:



Leakage reactance of core type transformer:

Let, L = Mean length of duct/air gap.

L_c = axial length of winding

b_s, b_p = radial width of 1^0 and 2^0 winding.

a = width of radial duct.

To find out the leakage reactance, the first of all, we need to find the flux leakages of windings.

The leakage flux of primary winding in the strip = Flux linkage of 1^0 wdg. In the strip (ψ_1)

So, the flux linkage of 1^0 wdg.,

$$\mathbf{\Psi_1 = \mu_0 (L_{mtp}/ L_c).\, I_p.\, T_p^2.\, (b_p/3)}$$

The leakage of flux of 1^0 wdg. Due to duct flux is,

$$\mathbf{\Psi_0 = (1/2)\, \mu_0 (L_0/ L_c).\, I_p.\, T_p^2.\, a}$$

So, the total flux linkages of 1^0 wdg. is,

$$\mathbf{\Psi_P = \mu_0 (L_{mtp}/ L_c).\, I_p.\, T_p^2.\, (b_p/3) + (1/2)\, \mu_0 (L_0/ L_c).\, I_p.\, T_p^2.\, a}$$

$$\psi_P = \mu_0.\, I_p.\, T_p^2 / L_c\, [L_{mtp}\, .\, b_p/3 + L_o\, .a/2]$$

Take, $L_{mtp} = L_o = L_{mt}$

$$\mathbf{\psi_P = \mu_0.\, I_p.\, T_p^2 (Lmt/ L_c)\, [b_p/3 + a/2]}$$

So, the leakage inductance of 1^0 winding is,

$$\mathbf{L_P = \psi_P / I_P = \mu_0 . T_p^2 (Lmt/ L_c) [b_p/3 + a/2]}$$

Total leakage reactance of 1^0 winding in core type transformer is,

$$x_P = 2\pi f. L_p$$

$$\mathbf{x_P = 2\pi \mu_0 . T_p^2 (Lmt/ L_c) [b_p/3 + a/2]}$$

Similarly, the total leakage reactance of 2^0 winding of the transformer is,

$$\mathbf{x_s = 2\pi \mu_0 . T_s^2 (Lmt/ L_c) [b_s/3 + a/2]}$$

Total leakage reactance of Transformer referred to 1^0 side, X_P is

$$X_P = x_p + x_s / K^2 = x_p + x_s (T_P / T_s)^2$$

$$\boxed{\mathbf{X_P = 2\pi \mu_0 . T_P^2 (Lmt/ L_c) [(b_P + b_s)/3 + a]}}$$

c) No Load Current: The no-load current I_0 consists of two components: i) magnetizing component I_μ and ii) loss component (I_L) and its value is given by $Io = [I_\mu^2 + I_L^2]^{1/2}$

Thus the estimation of I_o required the calculation of its two components.

Let, l_c, l_y = length of flux path through core limb and core yoke respectively, m

$$(l_c = H_w , l_y = W)$$

at_c, at_y = mmf/metre for flux densities in the core and yoke.

So, total magnetizing mmf of core is,

$$\boxed{\mathbf{At_c = 2\ at_c . l_c + 2\ at_y . l_y + \text{mmf required for joints}}}$$

So, RMS value of magnetizing current is,

$$\boxed{\mathbf{I_\mu = AT_c / (\sqrt{2}\ T_p)}}$$

or,

$$\boxed{\mathbf{I_\mu = AT_c / (K_{pk} . T_p)}}$$

where, K_{pk} = peak factor.

Let the iron losses be Pi, the loss component of current is,

$$\boxed{\mathbf{I_L = P_i / V_p}}$$

d) Magnetizing volt-amperes: As emf of 1^0 wdg. is,

$$E_p = 4.44 . f . T_p . B_m . A_i$$

So, magnetizing volt-amperes is,

$$(VA)_m = E_p * I_m$$

$$\boxed{\mathbf{(VA)_m = 4.44 . f . B_m . A_i (AT_o) / \sqrt{2}}}$$

Now AT_o = magnetizing mmf per metre x length of path in iron = at_m x l_i $\mathbf{(VA)_m = 4.44 . f . B_m . A_i . at_m . l_i / \sqrt{2}}$

So, $\boxed{\mathbf{(VA)_m = 4.44 . f . B_m . A_i . at_m . l_i / \sqrt{2}}}$

Various losses in a Transformer and its efficiency: In a transformer as it is a static in nature, no motional/frictional losses/ windage losses are there in it. Hence the only losses occurring are:-

I) Iron/ Core Losses: It includes both hysteresis and eddy current losses.

Because the core flux Φ_{max}/ B_{max} is constant in the core of transformer, for all loads, the core losses are also same, at all loads, varies from 1% to 3% from no-load to full load

$$\text{Hysteresis loss, } W_h = P_h . B_{max}^{1.6} . f^x . V \text{ watts}$$

$$\text{Eddy Current loss, } W_e = P_e . B_{max}^2 . f^2 . t^2 . V \text{watts}$$

$$\text{Total iron losses, } W_i = W_h + W_e \text{watts}$$

The hysteresis losses are minimised by use of steel with high silicon content for the core and the eddy current losses are minimised by using very thin lamination on silicon steel stamping core of varnish.

Here, P_h = proportionality constant, depends upon volume, quality of core material.

P_e = proportionality constant, depends upon volume, resistivity of core material

x = called as Steinmetz constant = 1.5 to 2.5

I) Copper Losses: This is due to ohmic resistance of the transformer windings.

Total copper losses = $I_p^2 r_p + I_s^2 r_s = I_p^2 r_{0p} = I_s^2 r_{0s}$

$$\text{Total copper losses} = I_p^2 r_p + I_s^2 r_s = I_p^2 r_{0p} = I_s^2 r_{0s} \quad \text{watts}$$

$$\text{Total copper losses } \alpha \ I^2 \text{ or } (kVA)^2$$

The total iron losses can be found by conducting the open-circuit test and total copper losses by short-circuit test on a transformer.

Other losses which occur in a transformer are:-

i) Stray losses: Leakage flux in a transformer produces eddy currents in the conductors, tanks etc. These eddy currents produce the losses called stray losses.

ii) Dielectric losses: Dielectric losses occur in the insulating materials in the

transformer, i.e. in the transformer oil and solid insulating materials of transformer. These losses are significant only in high voltage transformer.

Efficiency of a transformer: The efficiency of a transformer, at a load and a power factor is defined as:

Efficiency, η = (output power) / (input power), (both are in same units W/kW)

or, η = (output power) / (output power + losses)

or, η = (output power) / (output power + iron losses + copper losses)

or, η = (input power - losses) / (input power) η = (input power - losses) / (input power)

η = 1- (losses) / (input power)

or,

$$\eta = (\text{input power - losses}) / (\text{input power})$$

$$\eta = 1 - (\text{losses}) / (\text{input power})$$

As the efficiency, η, depends upon the power output and input in watt, not in VA. So, η at any VA, depends upon the power factor (Cos Ø), being maximum at a power factor of unity.

UNIT-III

Q. 5 a): Mention various standard specifications of three-phase induction motor. Derive the various output equation.

b): Obtain and explain equivalent circuit of single-phase induction motor. Derive the torque expression.

Sol:

a) Standard specifications of 3-phase induction motor: The main specifications of a 3-phase induction motor for design purpose are:

1. Rated Output in H.P. or kW.
2. Three phases.
3. Frequency in Hz = f.
4. Voltage in Volts = V
5. Connections: Star Y or Delta Δ
6. Speed in RPM = N
7. Type: Squirrel Cage rotor or Wound rotor.
8. Type of duty.
9. Power factor
10. Efficiency.
11. Class of insulation.
12. Temperature rise.
13. Full load current.
14. Pull out torque.

Output equation: Now, we have to relate the output of machine and its main

dimensions.

Let, E_{ph} = induced emf per phase in volts (= applied voltage per phase)

I_{ph} = current per phase, A

T_{ph} = no. of turns per phase

Φ = Flux per pole in the air gap

p = no. of poles.

K_w = Winding factor

B_{av} = average value of flux density in the air gap.

ac = Ampere conductors per meter of the armature periphery

D = armature diameter or Stator bore dia., m

L = stator core length, m

n_s = synchronous speed, rps

η = full load efficiency

Cos Ø = full load power factor

τ = pole pitch = $\pi D/p$

kVA rating of 3-phase induction motor is given by

$kVA = 3 \times E_{ph} \times I_{ph} \times 10^{-3}$

or, $$kVA = 3 \times 4.44\, K_w\, f\, \Phi\, T_{ph}\, I_{ph} \times 10^{-3}$$

1. Specific magnetic loading (Bav):

B_{av} = Total flux in the air gap / (area of flux path in the air gap)

$$\mathbf{B_{av} = (p\,\Phi) / (\pi D L)}$$

2. Specific electric loading (ac):

ac = total armature ampere conductors / armature periphery at the air gap

$$\mathbf{ac = 3 \times 2 \times I_{ph} \times T_{ph} / (\pi D)}$$

3. Frequency (f):

Frequency, $f = (n_s . P) / 2$ Hz

So, $\Phi = B_{av} (\pi D L) / p$

& $I_{ph} \times T_{ph} = ac (\pi D) / 3 \times 2$

Thus, $$kVA = (1.11 \times \pi^2 \times B_{av} \times ac \times 10^3) \times D^2 L n_s$$

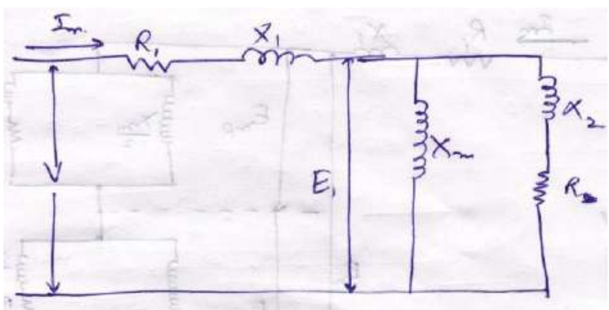
or, $$kVA = C_o \times D^2 L n_s$$

where, $\mathbf{C_o = (1.11 \times \pi^2 \times B_{av} \times ac \times 10^3)}$

Hence, the above kVA equation is called as output equation of an induction motor and called C_o is called as output coefficient.

a) Equivalent Circuit of 1-phase Induction motor: The equivalent circuit of a 1-phase induction motor can be drawn using either double field revolving theory or cross-field theory. However, most of induction motors have equivalent circuit based on the double field revolving theory, as 1-phase motors are 2-phase motors.

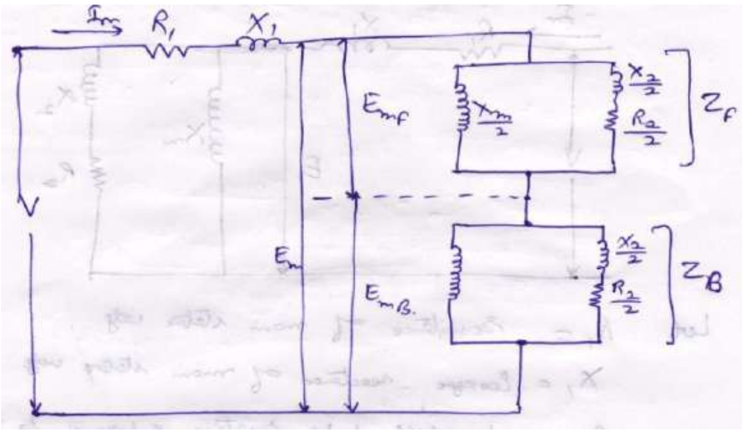
During the starting period, both the windings are connected in parallel circuit. When the motor reaches a certain speed, the auxiliary winding is disconnected from the supply and the motor running with only the main or running winding. The main/ running winding is considered as true 1-phase motor winding. To draw the equivalent circuit, the motor running with only the running winding is considered. When the motor is at rest, the main winding is excited, the motor behaves as a 1-phase transformer, whose secondary has been short-circuited. The equivalent circuit with the stationary motor is as drawn:



Let, R_1 = resistance of main stator winding

X_1 = reactance of main stator winding
R_2 = standstill rotor resistance referred to the main winding
X_2 = standstill rotor reactance referred to the main winding
X_m = magnetizing reactance.
V = applied voltage
I_m = main winding current.

As the pulsating air gap flux in the motor can be resolved into two equal and opposite magnetic fields within the motor according to double-field revolving theory, the magnitude of each rotating flux in one half of the alternating flux. Each field (main and auxiliary windings) produces resistive and reactance voltage drops in the rotor circuit. So, the motor can be considered as having a single stator with two imaginary rotors rotating in opposite directions. The standstill impedance of each rotor referred to the main winding is (R_2/ 2 +j X_2/ 2). So, the equivalent circuit of 1-phase induction motor with stationary rotor is as shown:

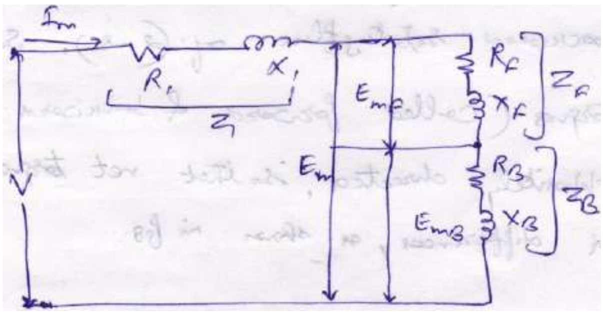


The forward and backward impedances are as given:

$$Z_F = R_F + j X_F = [(R_2/2s + jX_2/2)(jX_m/2)] / [(R_2/2s + jX_2/2) + (jX_m/2)]$$

$$\& \quad Z_B = R_B + j X_B = [(R_2/2(2-s) + jX_2/2)(jX_m/2)] / [(R_2/2(2-s) + jX_2/2) + (jX_m/2)]$$

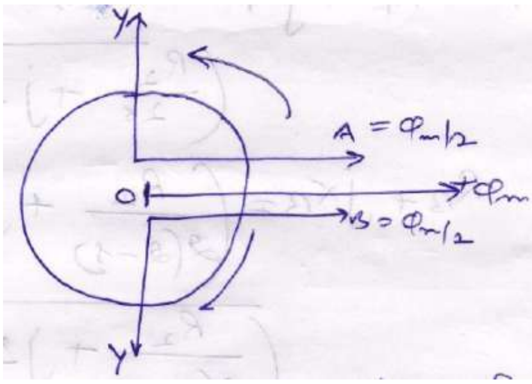
The simplified circuit of a single-phase induction motor with only running winding energized is as shown in fig. The current in the stator winding is given by:



$$I_m = V / (Z1 + Z_F + Z_B)$$

Torque in a 1-phase induction motor: As in the 1-phase induction motor, double field revolving theory is considered, in which an alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously (N_s = 120 f/p) in opposite direction.

Let the alternating flux Φ have a maximum value of Φ_m. Its component fluxes A and B will each be equal to Φ_m / 2 revolving in anticlockwise and in clockwise directions respectively, as shown:



One of component of these fluxes has a slip 's' with respect to the forward rotating flux (i.e. one which rotates in the same direction as rotor) and other component of flux has a slip with respect to backward rotating flux of (2-s). So the two torques called forward and backward torques, are oppositely directed, so that net torque is equal to their differences, as shown in fig.

As power developed by the rotor in an induction motor is given by:

$P_g = [(1-s)/s]\, I_2^2 R_2$

& gross torque is given by with N= speed of motor.

$\mathbf{T_g = (1/2\pi N) \times P_g = (1/2\pi N) \times [(1-s)/s]\, I_2^2 R_2}$

As $N = N_s(1-s)$

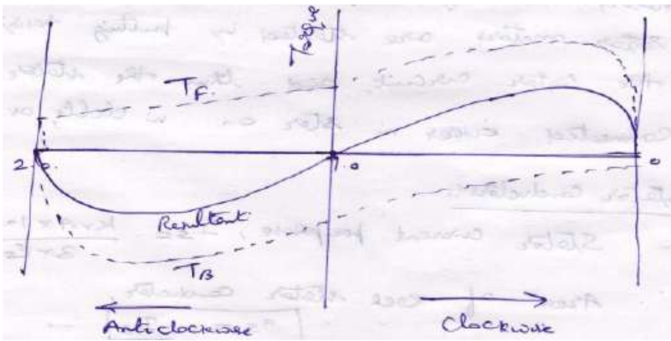
Thus, $\mathbf{T_g = (1/2\pi\, Ns)\, I_2^2 R_2 / s = k \times I_2^2 R_2 / s}$

Hence the forward and backward torque expressions are given by:

$T_F = k \times I_2^2 R_2 / s$

& $T_B = - k \times I_2^2 R_2 / (2-s)$

and, total torque, $T = T_F + T_B$



Q. 6 a): How conductor size and terms, number of slots and slot designs are decided in the case of three phase induction motor?

b): Discuss the roles of main and auxiliary windings in the case of 1-phase induction motor. How are these designed?

Sol:

a) Stator winding: The windings used for induction motor stators are single layer mush windings and double layer lap windings. Mush winding is most common for small motors. Medium size motors use double layer lap windings with diamond shaped coils. For large motors or those for high voltage, the stator phases may be formed by single-layer concentric coils. The three phases of the winding can be connected in either star or delta depending upon starting methods employed. The squirrel cage motors are usually started with star-delta starters and thus, their stators are designed for delta connection. The wound rotor motors are started by putting resistance in the rotor circuit and thus the stator can be connected in either in star or in delta as desired.

Stator conductors: Stator current per phase, $I_s = kVA \times 1000 / (3 \times E_s)$

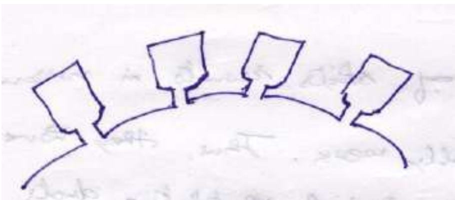
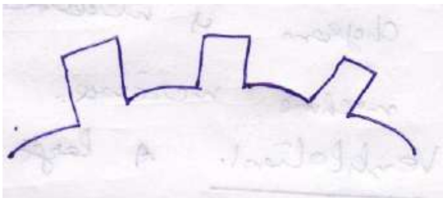
So, **area of the each stator conductor, $a_s = I_s / \delta_s$**

where, δ_s = current density in the stator conductors.

The current density of the stator conductors, δ_s is usually assumed between 3 to 5 A/mm^2. Round conductors would be convenient only if area of the cross section is well below 8 or 10mm^2. For conductor area above 10mm^2, strip conductors are selected, thus giving a better space factor for the slots.

Stator Slot design: The shape, size and no. of slots has an important bearing on the performance of an induction motor.

Shape of stator slots: Two types of slots are generally used, a) Semi-closed slots, b) open slots.

Semi-closed Slots	Open Slots
1. Air gap contraction factor is small giving a small value of magnetizing current. Low tooth pulsation loss and quiet operation. 	1. The use of open slots avoids excessive slot leakage, thus reducing the leakage reactance. 
2. Semi-closed slots are generally tapered having parallel sides teeth arrangement	2. Open slots are normally parallel sides having tapering teeth arrangement.
3. Semi-closed slot is useful for small motors having round conductors. For a given value of tooth flux density, this arrangement provides maximum slot area. Under this, the coil must be tapered and insulated after they are placed in the slots.	3. Open slots are useful for large and medium motors having strip conductors. Under this the coils can be formed and insulated before they are just dropped into the slots.

Number of Stator Slots: The following points are considered before selecting the no. of stator slots:-

I) Tooth pulsation loss: In motors with open slots, the slot openings have a considerable influence on the air gap reluctance. The slots should be so proportioned that minimum variations in the air gap reluctance are produced. These effects can be minimized by using a large no. of narrow slots.

ii) Leakage reactance: If there is a large no. of slots, there are larger no. of slots to insulate and thus the width of insulation becomes more and the leakage flux has a longer path through air which results in leakage flux's reduction. Thus with large no. of slots, the leakage flux and leakage reactance is reduced. Thus diameter of the circle diagram for power output is increased and thus overload capacity of machine increases.

iii) Ventilation: A large no. of slots results in narrow teeth making them mechanically weak. Thus, they have to be supported at the radial ventilating ducts obstructing the flow of air.

iv) Magnetizing current and iron losses: As discussed above, the teeth section of slots is reduced due to large no. of slots. So, this may results in excessive flux density in teeth, giving rise to high I_m and core losses.

v) Cost: With larger no. of slots, there are large no. of coils to wind, insulate and install involving higher cost.

In general, the no. of slots should be so selected to give an integral no. of slots per pole per phase. Generally, for small and medium size machines, the no. of slots per pole per phase lie between 3 to 5. The narrow range is 3 to 4. The slot pitch at air gap surface for open slots should lie between 15 to 25mm and for semi-closed slots, may be less than 15mm.

Let S_s = no. of stator slots

then, stator slot pitch = air gap surface / S_s

$$\text{stator slot pitch} = \pi D / S_s$$

Total no. of stator winding conductors = 3 x2 x T_s

$$\text{No. of conductors per slot, } Z_{ss} = 3 \times 2 \times T_s / S_s$$

Size/Area of stator slots: When the no. of conductor per slot has been defined, an approximate area of stator slot is,

$$\text{Area of stator slot} = \text{copper area per slot / space factor} = Z_{ss} \times a_s / \text{space factor}$$

The value of space factor varies from 0.25 to 0.4. lower value of space factor to be selected for higher voltage machines to allow more space for insulation.

a) Role of Main/ Running winding and its design: The stator winding of 1-phase induction motors are concentric type. These are usually 3 or more coils per pole each having same or different no. of turns. The arrangement of winding is governed largely by the necessity of minimizing harmonic fluxes which may otherwise give rise to noise and uneven accelerating torque. Such harmonics are produced owing to non-sinusoidal shape of mmf wave. Mmf wave harmonics can be reduced by utilizing 70 percent of total slots for running winding as this arrangement gives minimum low order harmonics. The remaining slots are used for accommodating the starting or auxiliary windings. In a small 1-phase motor, may be desirable to reduce the harmonics still further by grading the windings i.e. by having no. of conductors in each slot thereby an mmf wave which approaches a sine wave.

No. of turns in running winding: The number of turns in the running winding can be calculated as:

Stator induced voltage, $E = 4.44 f \Phi_m T_m K_{wm}$

where, T_m = no. of turns of main winding

K_{wm} = winding factor for main winding

No. of turns in the main/ running winding is,

$$T_m = E / (4.44 f \Phi_m K_{wm})$$

where, Φ_m = flux per pole = Bav x (π D L/ p)

The winding factor K_{wm} can be assumed between 0.75 to 0.85.

No. of turns in series per pole for main winding is,

$$\mathbf{T_{pm} = T_m / p}$$

Running winding conductors: Current carried by each running winding conductors is,

I_m = (h.p. x 745) / (Vh CosØ)

$a_m = I_m / \delta_m$ Area of main winding conductors is,

$$a_m = I_m / \delta_m$$

Role of Starting/ Auxiliary winding and its design: After a satisfactory main winding design, the next step is to design a suitable staring or auxiliary winding. In order that the starting winding can produce a revolving field, the flux set up by it must be out phase with flux set up the main winding. The no. of turns of main winding must satisft thee requirements of the core and the size of conductors requirements of the load. Thus reactance, X of the main winding is high and resistance R is low. The starting winding must have parameters just the reverse of those of the main winding.

The auxiliary winding is also of the concentric distributed winding and is arranged as the main winding but spaced in quadrature with reference to the main winding. With resistance split phase motors, the required resistance is usually obtained by using a small section of wire. The current density at starting may be as high as 100A/ mm^2. The phase angle between the starting winding current and the line voltage should be about 0.4 of that of the main winding.

UNIT-IV

Q. 7 Write technical note on various optimization techniques and their applications in electrical machine design.

Sol:

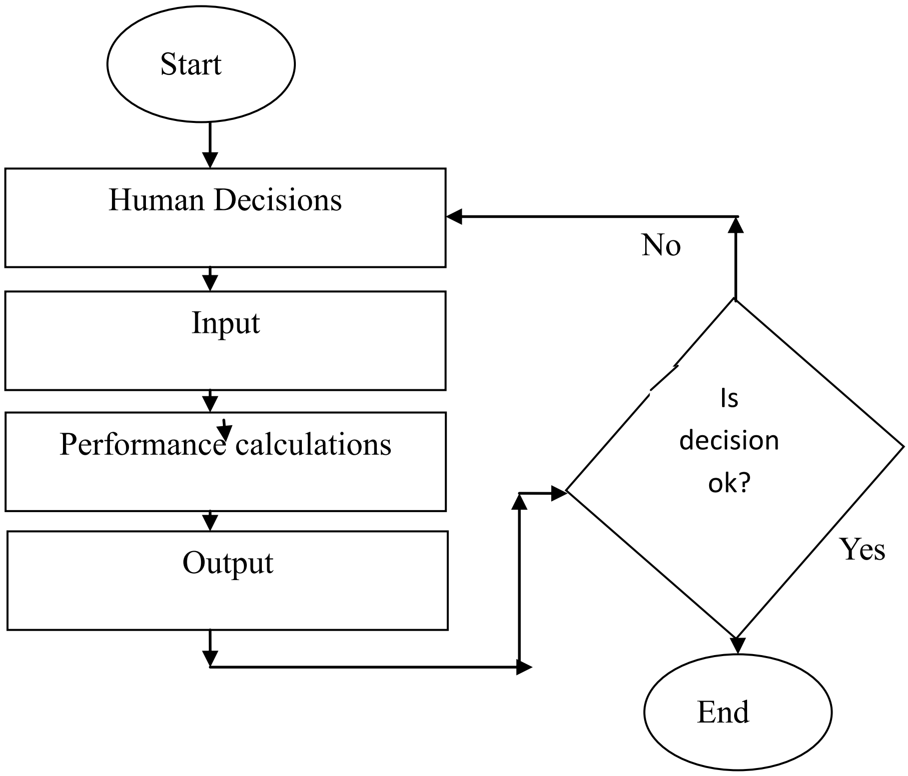
Computer Aided design-Different optimization approaches: The application of digital computers to the problem of electrical machine design was first introduced in 1950. In the early stage, this was limited to design of transformers. In the year 1956, the applications of digital computers are discussed to the design of transformers as well as rotating machines. In the same year, Veinatt published a research of application of digital computers for the design of induction motors. A flow chart was developed giving basic procedure for the design of polyphase induction motor. This paper in fact developed the analysis method for the design of polyphase induction motor.

The concept of optimization in electrical machine design was introduced by Godwin in 1959 and a program was developed for design of squirrel cage induction motors. In 1959, Heroz introduces the concept of two commonly acceptable approaches to machine design, namely:

I) Analysis method and ii) Synthesis method.

I) Analysis Method: The analysis method of design is depicted as in fig. In this method, the choice of dimensions, materials and type of construction are made by the designer and these are presented as input data to the computer. The performance was calculated by the computer and is returned to the designer for examination. The designer examines the performance and makes choice of input, if necessary and performance is recalculated. This procedure is repeated till the performance requirements are satisfied.

The use of term "analysis method" means the use of computer for the purpose of analysis leaving all exercises of judgement to the designer.



The advantages of analysis method are:-

I) Easy to program, to use and to understand.

ii) It results in time saving thereby giving quick returns on investments.

iii) Programs are simple.

iv) Highly acceptable results of analysis method by the designers.

I) Synthesis Method: The synthesis method is as depicted in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

The greatest advantage of synthesis method is as the saving in time in lapsed time and in engineering man hours on account of the decision left to the computer itself.

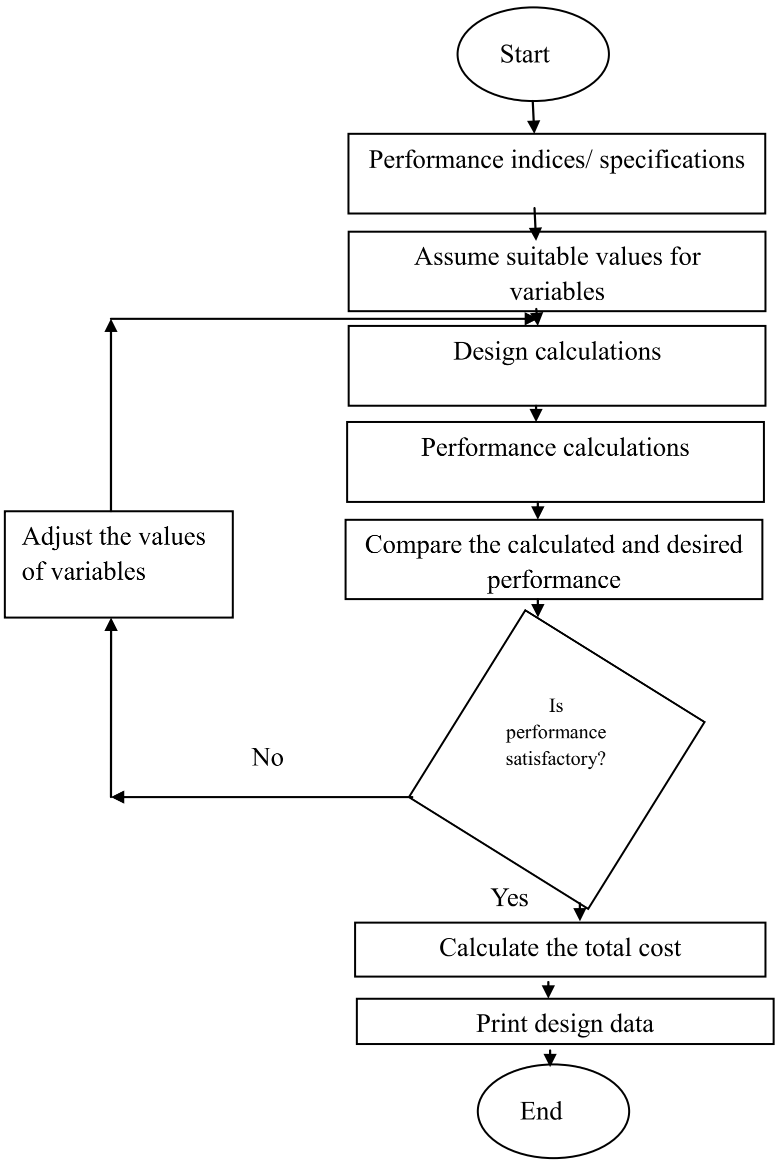
The synthesis method suffers with a number of serious disadvantages such as:-

1) This method involves too much logic since the logical decisions are left to the computer to take. Now, these logical decisions have to incorporated in the program and before, incorporation, the team of design engineers are to agree upon them.

2) The logical decisions to arrive at a optimum design are too many and then, there are too many people with too many ways to suggest to produce the optimum design and thus, it becomes really hard to formulate a logic for obtaining an optimum design.

3) The formulation of a synthesis program taking into account of factors listed would make it too complex. So, cost of computer program becomes high and thus use of a large computer and also large running time involves huge expenditure.

4) The synthesis program formulated at a high cost cannot be used for ever, as due to changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions etc., the program has to be changed and up dated keeping. Thus synthesis method requires additional efforts and cost in order for the above.

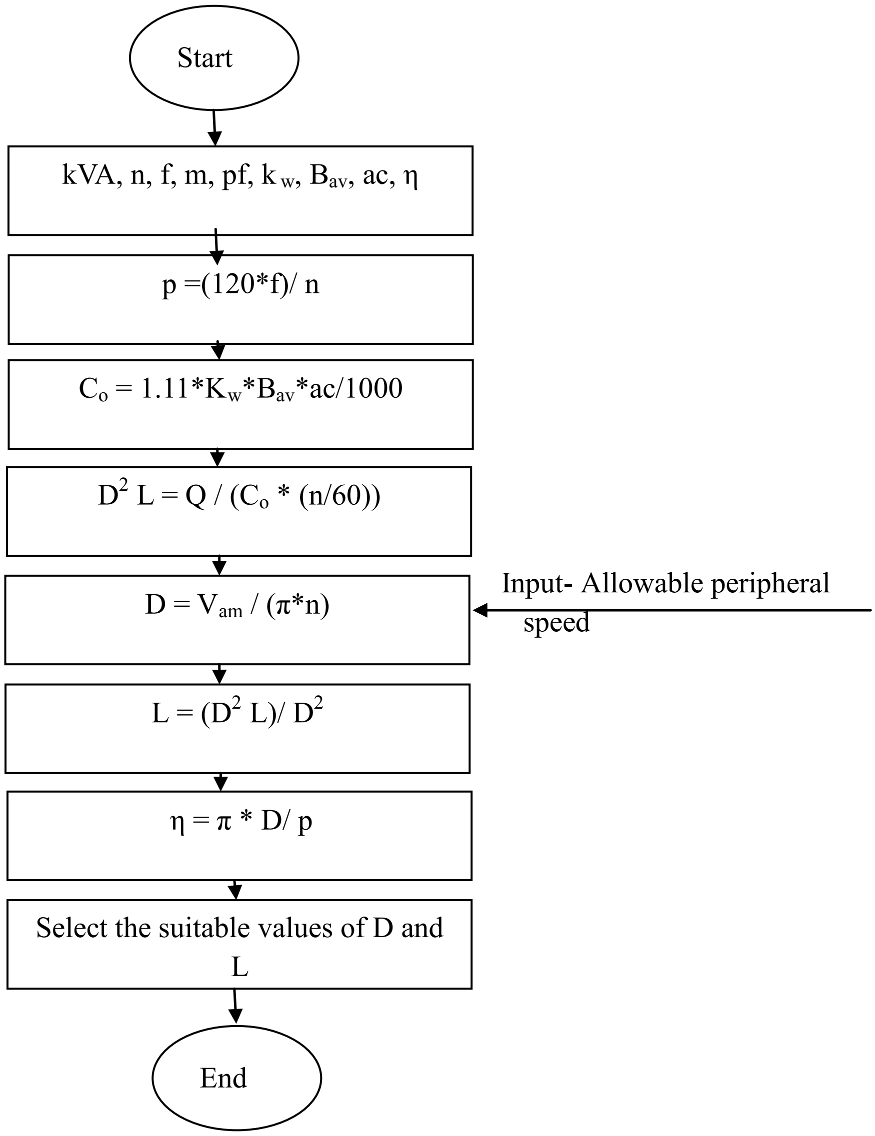


Q. 8 Discuss the Computer Aided design of synchronous machines.

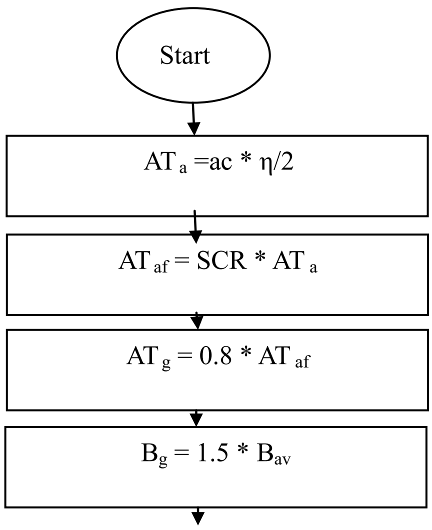
Sol:

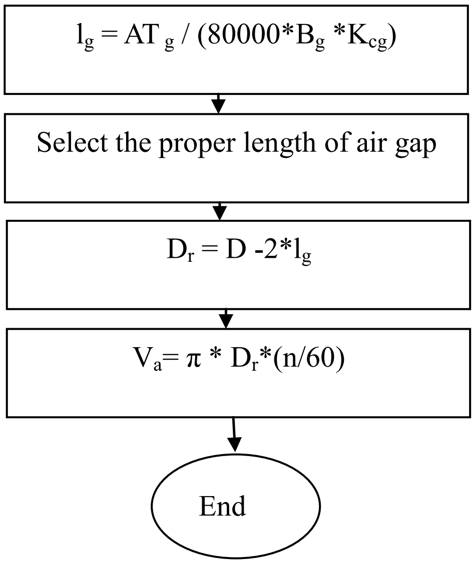
Computer Aided design of synchronous machine (Flow Charts):

I) Main dimensions:

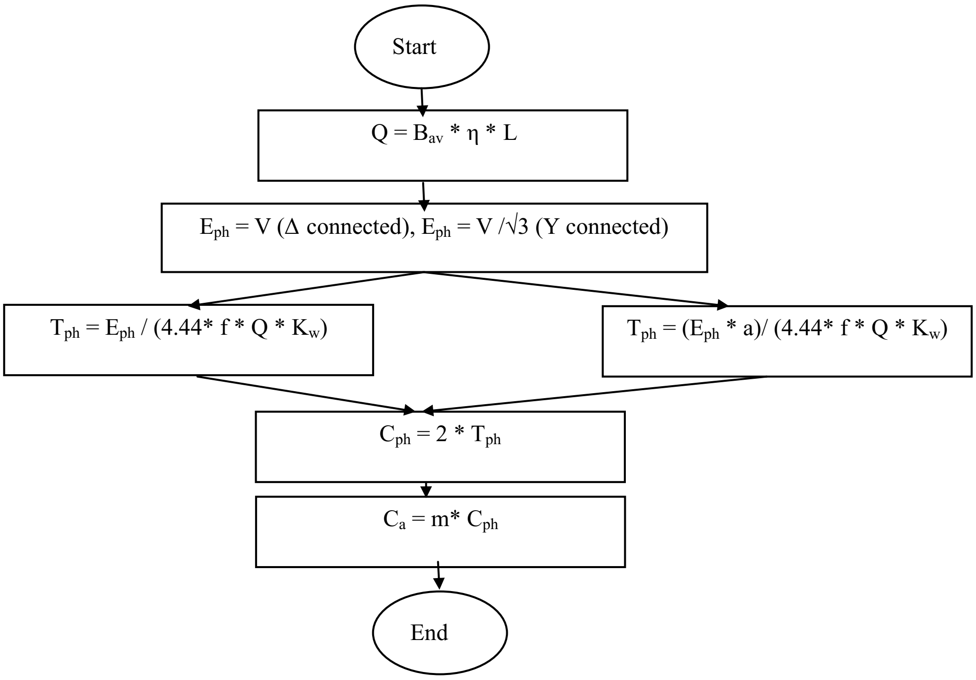


ii) Length of air gap:

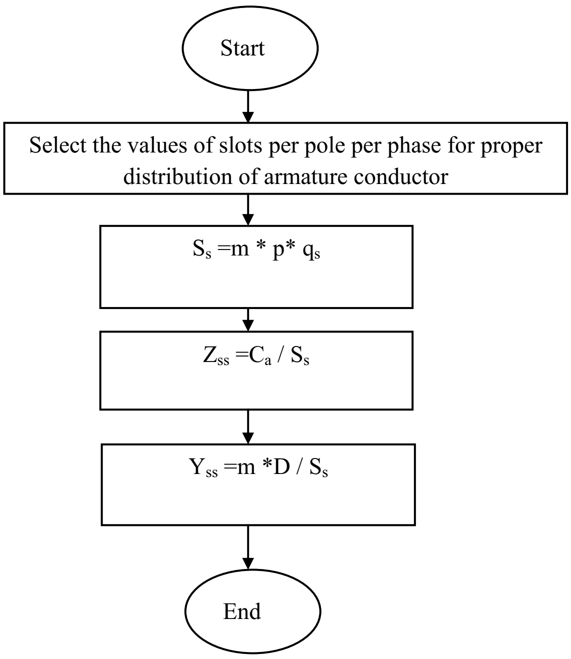




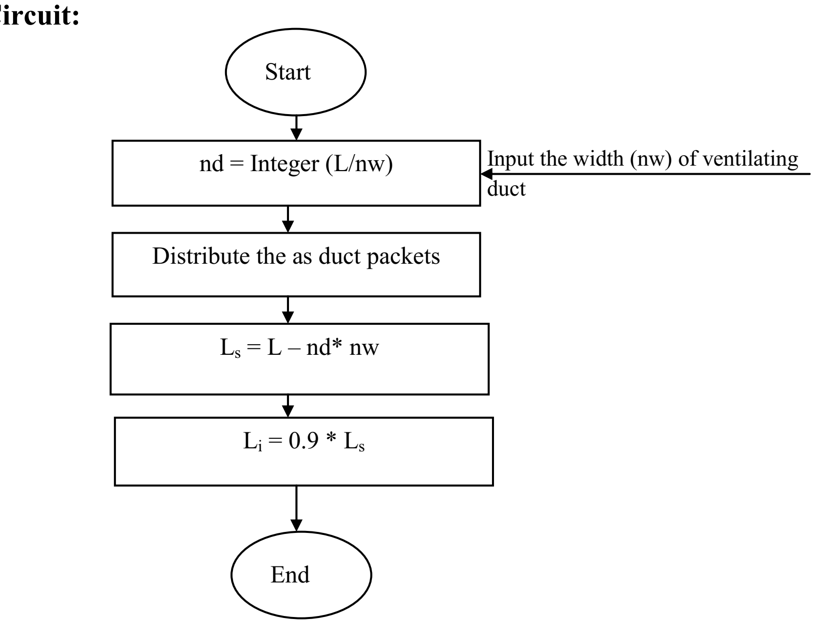
iii) Stator:



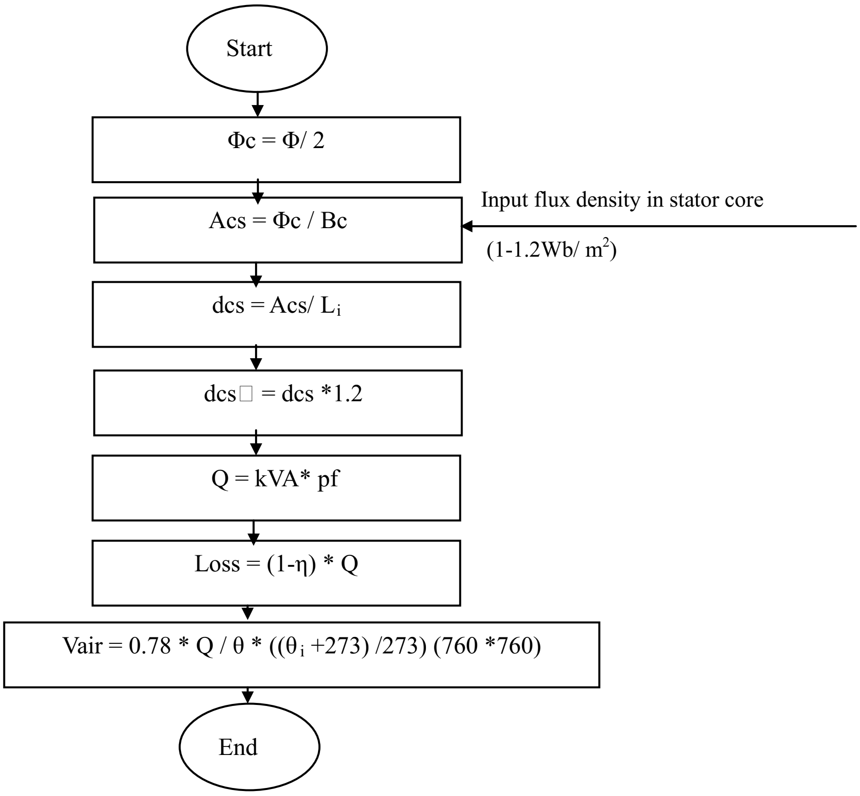
iv) Number of Slots:



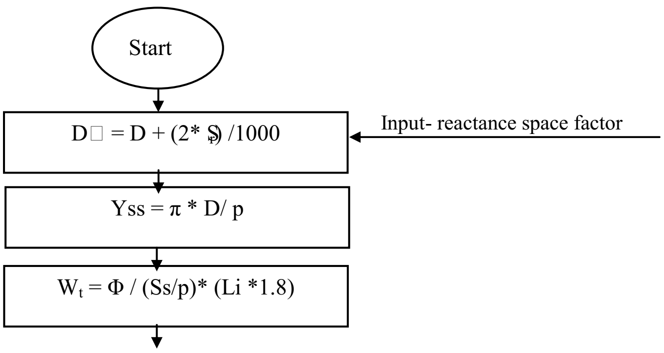
v) Magnetic Circuit:

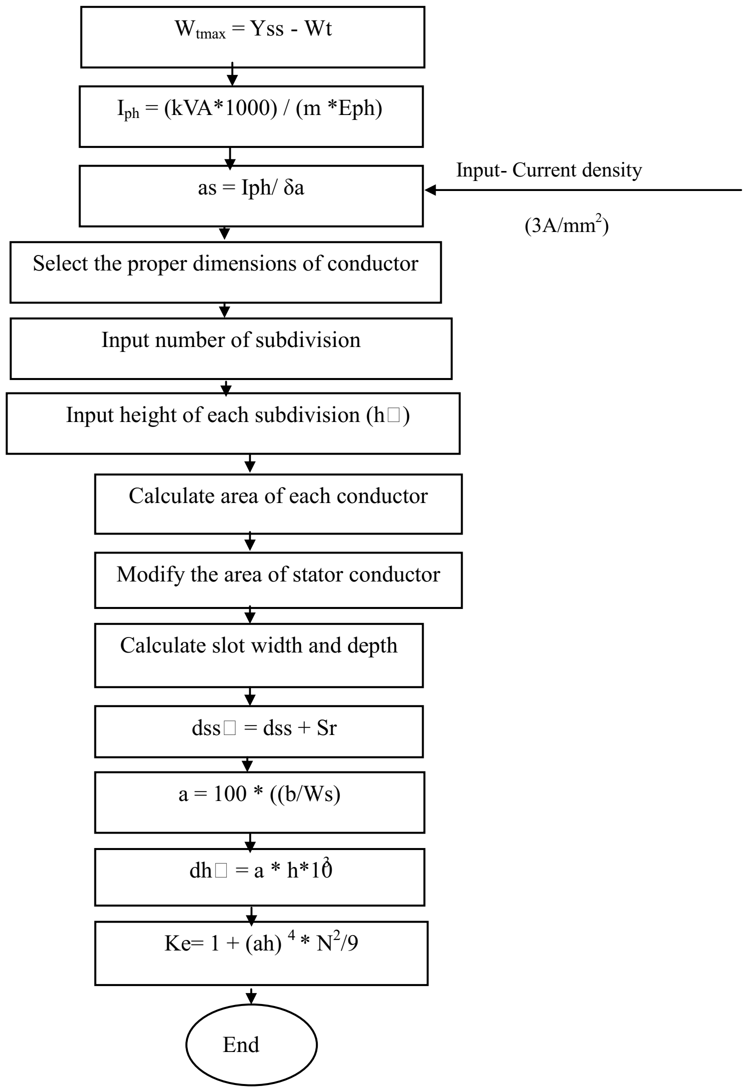


vi) Stator Core:

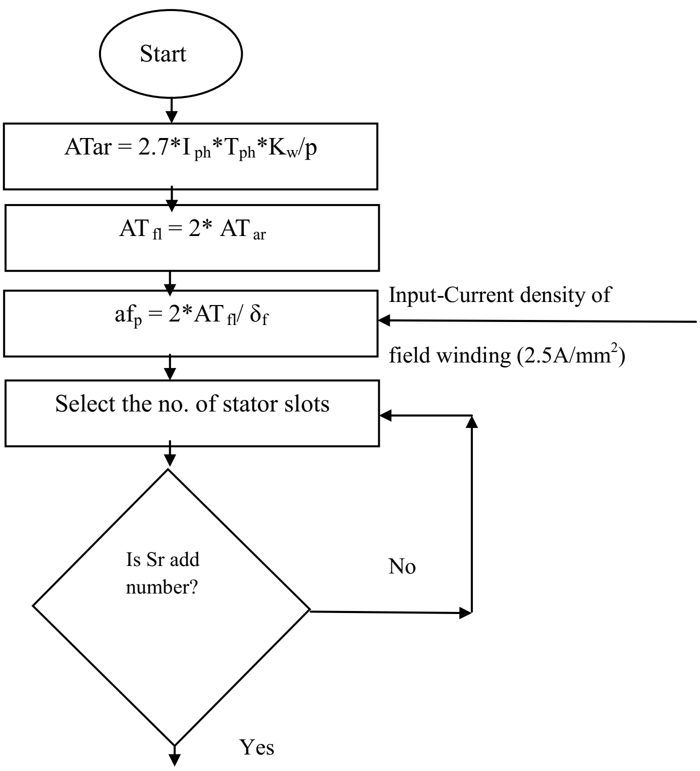


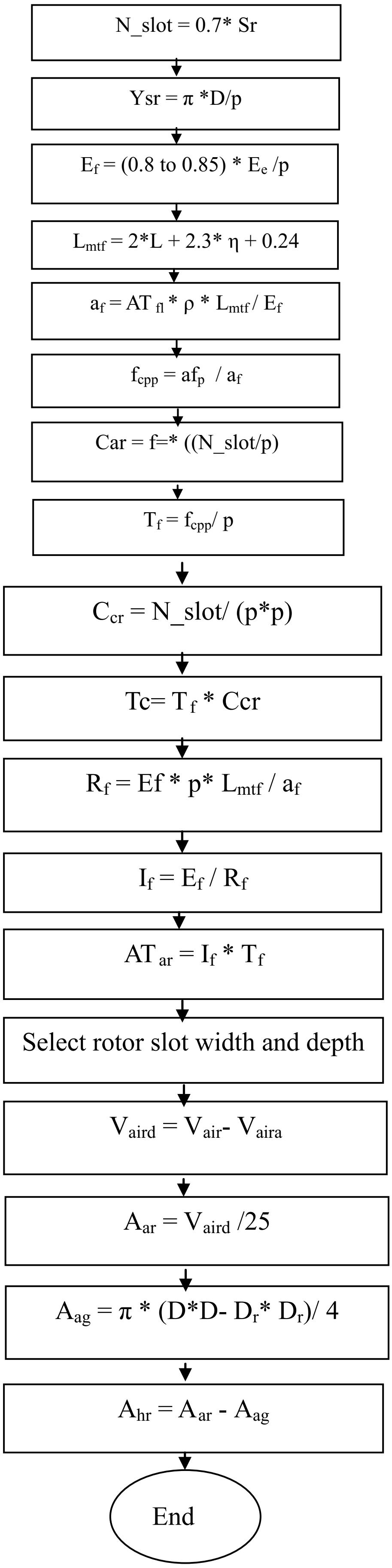
vii) Slot dimensions:





viii) Rotor design:




N_slot = 0.7* Sr
Ysr = π *D/p
E_f = (0.8 to 0.85) * E_e /p
L_{mtf} = 2*L + 2.3* η + 0.24
a_f = AT $_{fl}$ * ρ * L_{mtf} / E_f
f_{cpp} = af_p / a_f
Car = f=* ((N_slot/p)
T_f = f_{cpp}/ p
C_{cr} = N_slot/ (p*p)
Tc= T_f * Ccr
R_f = Ef * p* L_{mtf} / a_f
I_f = E_f / R_f
AT_{ar} = I_f * T_f
Select rotor slot width and depth
V_{aird} = V_{air}- V_{aira}
A_{ar} = V_{aird} /25
A_{ag} = π * (D*D- D_r* D_r)/ 4
A_{hr} = A_{ar} - A_{ag}
End

Electrical Machine Design

SOLVED QUESTION PAPER-3

Note: Attempt Five questions in all, selecting one question from each unit. All question carry equal marks.

UNIT-I

Q. 1 a): Discuss the modern trends and machine manufacturing techniques in the design of electrical machines.

b): Discuss what the various methods of cooling?

Sol: a):

Modern trends in design of electrical machines: The design of electrical machines is both a science and an art. A "science", because it follows universally and established adopted physical and mathematical principles, which have been verified by the experimental results and methods and an "art" is that the knowledge of these principles is often insufficient to produce a correct and economic design. This can be achieved by correct decisions based upon judgement and intuition and through understanding of the subject. The design of electrical machines consists of the solution of many complex and diverse engineering problems and normally these problems are loosely interrelated to a lesser or a greater degree. In fact the design of electrical machines presents a mathematically indeterminate problem with many solutions. The design of electrical machines at the first requires the choice of constructional scheme to the desired machine performance and types of construction of its basic machine parts preliminarily, it is also required to choose a system of cooling and ventilation of machine, materials for the magnetic system, insulating materials and the conduction materials etc. The overall design process, right from the specifications, requirements to the determination of machine dimensions and other items of information required for the manufacture of both static and rotating machines. The process of design of a single machine may be divided into three major design problems such as:

i) Electromagnetic design,

ii) Mechanical design

iii) Thermal design

These above problems may be solved separately and the results thus obtained, combined later on. Each of these three major problems may further be broken down into simpler and loosely related elements. Each element may be considered as a separate problem and thus, procedure of solution of elements involves. The other aspect of the modern day design of electrical machine is designing of number of machines, all of which form a part of a single system, e.g. generators, motors and transformers form a part of an electromechanical energy network. The different machines of such a system are interconnected and react upon each other, sometimes considerably and disastrously. So the machines for such a system cannot be designed in isolation and the design of all the machines have to be completed concurrently, since the design of one machine depends on that of the other.

Sometimes, it is desired to design a series of machines having different ratings to fit into a single frame size. In this case, the finished designs of machines must be produced in groups, where all designs within a group are interdependent. Both the cases are an optimization problem. So, the optional solution involves iterations wherein values of variables are designed to satisfy both the performance and cost. So, it is clear that the design of electrical machine is an iteration process wherein the assumed data may have to be varied many a times to achieve a desired design. So, the evolution of design to meet the optimum criteria is a matter of long and tedious iterations and applications of fast digital computers are used in design of electrical machines. The digital computer has completely revolutionized the field of electrical machine design. The computer aided design has the advantage, eliminating tedious and time consuming hand calculations. This accelerates the design process. In addition, computer aided design permit more detailed and precise functional relationships which lead to new and comprehensive design procedures.

Modern Machine Manufacturing Techniques: As the electric power has wide and diverse applications in all fields of human activities and thus utilization of electric power is growing up day by day. So, there is a need of increased generation capacity and thus, constructions of new electric power stations are required. This necessitates a great need of a variety of electric machines over a wide range of power outputs. This growing need of power generation and power utilization have to be met by expanding continuously electrical machine manufacturing industry applying modern manufacturing techniques. The modern machine manufacturing trends are:-

1. The modern electrical machines are characterised by a very wide range of power outputs. The power range varies from a fraction of watt to several hundreds of megawatt in a single unit and also of power is 1: 10^{10}.

Similarly, the range of rotational speeds of electrical machines is very wide ranging from speed of few revolutions per second to several thousand revolutions per second. Thus, these lead to a variety of types of constructions and the type of construction adopted is classified by constructional features and their subdivision. A broad classification of electrical machines can be made based on power output and rotational speed ranges:-

a) Small size machines: Electrical machines having a power output of 750W may be called as small size machines.

b) Medium size machines: Medium size machines have a power output range of few kilowatts to 250kW.

c) Large size machines: Large size machines have a power output ranging from 250kW to 5000kW. These machines are usually designed and manufactured as a series and have a definite power range.

d) Larger size machines: These special machines are designed and manufactured on special order on customer's demands. So, these are designed on individual basis. The power output of these machines is very high as hundreds of megawatts.

Similarly, the above machines are also influenced by the operating speed of the machines, e.g. for small machines having speed, 250rpm, have large diameter and small axial length, while high speed machines of range 3000rpm and above, has small diameter and longer axial length.

2. The second important feature of modern machine manufacturing is the trend of build machines, smaller in size and thus, involves the use of lesser material and at the same time, has high efficiency and overload capacity. This can be achieved by following technological achievements:

a) There has been considerable development and refinement in constructional techniques and arrangement of conductors and thus there is a drastic reduction in stray load losses.

b) There has been a vast development in the cooling and ventilations systems.

3. The third important factor in the use of magnetic materials, which has a high permeability, a low iron losses and a high mechanical strength. These materials permits a high a value of flux density and size of machine reduces with increase in power output.

4. There has been a considerable improvement in the insulating materials. These insulating materials have ability to withstand high temperature stress. Thus, the power output of machine increases, as the power depends considerably on insulating materials. So, better class of insulating materials allow the machine size to reduce with more power output.

5. Modern machine designs are marked with use of higher electro-magnetic loading for active parts and high mechanical loading for construction material.

6. Modern electrical machines have a wide field of applications. They are used in varied environment and under different operating conditions. The design of machine and its manufacture should be such that it operates satisfactorily under the normal environmental conditions.

b) Various methods of cooling: The factors which determine the size of the machine or a given duty is the temperature rise, which occurs as a result of the various losses in the machines, such as iron losses, copper losses, dielectric losses, stray losses, windage & frictional losses etc. The losses generate heat and temperature rise inside the machine. The temperature rise if allowed to rise beyond the permissible limit depending upon the type of insulation used, will deteriorate the insulation and renders the machine useless. Thus, it is necessary to provide suitable ventilation and cooling for the machine, so that temperature rise of the machine does not go beyond the limit. The rating of an electrical machine consequently depends upon how fast the heat is transferred from inside the machine and dissipated to the ambient surroundings. Thus, for increasing the rating of machine, either insulating materials of higher temperature limit are developed and used or cooling techniques are employed. Small size machines of fractional h.p. range may be cooled by natural means, with no external device like fans and cooled by natural radiations. As the size of the machine increases, the losses and thus temperature rise increases faster than the increase in surface area and hence artificial cooling methods are necessary in order to avoid excessive temperature rise during machine operation.

In most cases, the cooling of machines is done by air streams and this cooling is called as "ventilation". In high speed machines, like turbo-alternators, hydrogen is used as cooling. There are machines, in which the water is used as cooling.

Cooling System: According to BIS (Beurou of International standards), the cooling systems are classified into three types depending upon the origin of cooling):-

1. **Cooling system/ Natural Cooling**: The machine is cooled by natural air currents set up either by rotating parts or due to temperature differences between the inside parts and the ambient air.

2. **Self Cooling**: The machine is cooled by cooling air driven by a fan mounted on the rotor or one driven by it.

3. **Separate Cooling**: The machine is cooled by a fan not driven by its shaft, but fan driven by a separate machine.

The cooling of machines, according to the manner of cooling, is of various types:

i) Open-circuit ventilation: The heat is given by directly to cooling air through the machine, the air is being continuously replaced.

ii) Closed-circuit ventilation: In this system. the heat is transferred through an intermediate cooling medium circulating in a closed circuit through the machine and a cooler.

ii) 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 mean or by air blown by fan.

iv) Liquid Cooling: Parts of the machine carry water of another kind of liquid like oil, flowing through them or they are immersed in a liquid.

v) Inner Cooling of windings: These are of two types:

a) Inner gas cooling: One or all windings are cooled by a gas, like hydrogen, flowing internally through the conductors or coils.

b) Inner Liquid cooling: One or all windings are cooled by a liquid, like water, flowing internally through the conductors or coils.

Q. 2 a): Discuss the output equation of DC machines. Explain with an expression, the choice of ampere conductors per metre in DC machines.

b): Determine the total commutator losses for a 800kW, 400V, 300rpm, 10-pole generator having the following data: commutator diameter-100 cm, current density in brushes- 0.075A/mm^2, bush pressure-14.7kN/m^2, coefficient of friction – 0.23, brush contact drop- 2.2V.

Sol: a):

Output equation of DC machines: The output equation of an electrical machine can be expressed in terms of its main dimensions, specific magnetic and electrical loadings and speed, the equation describing this relationship is as output equation.

<u>**DC Machine**</u>:

As power developed by armature in kW,

$$P_a = \text{generated emf x armature current x } 10^{-3}$$

But, $E = \Phi Z n p / a$

So, $P_a = \Phi Z n p / a \times I_a \times 10^{-3}$

$P_a = (p\,\Phi)\,[(I_a/a) \times Z]\, n \times 10^{-3}$

$$P_a = (p\,\Phi)\,[I_z \times Z]\, n \times 10^{-3}$$

P_a = (total magnetic loading) x (total electrical loading) x n x 10^{-3}

Here, specific magnetic loading, $B_{av} = (p\ \Phi) / (\pi\ D\ L)$ = (Total flux / area of each pole)

So, **$p\ \Phi = B_{av} \times (\pi D L)$**

& specific electric loading, $ac = (I_z \times Z) / (\pi D)$

= total ampere conductor / perimetry of armature

So, **$(Iz \times Z) = ac \times (\pi D)$**

Thus, power developed by the armature is, **$P_a = C_o . D^2.L.n$** $P_a = (1.11\pi^2 B_{av} \times ac \times 10^3) D^2 L n$

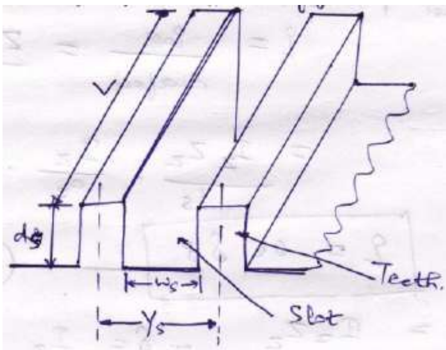
$P_a = C_o . D^2.L.n$

& **output coefficient, $C_o = 1.11\pi^2 x\ B_{av}$ x ac x10^3**

This is called as output equation of the dc machine.

Choice of ampere conductors per metre: The following factors influence the choice of ampere conductors per metre or specific electric loading (ac):-

1. **Permissible temperature rise**: An armature of a rotating machine is as shown in fig.



Let, Z= total no. of armature conductors.

S = no. of armature slots.

a_z= area of each conductor

ρ = resistivity of material

δ = current density

For a slot pitch Y_s, ampere conductors per metre are,

$a_z = (I_z \times Z) / (\pi D) = (I_z \times Z/S)/ (\pi D /S) = (I_z \times Z_s)/ Y_s$

where, Z_s = no. of conductors per slot.

Resistance of each conductor of slot portion = $\rho L / a_z$

So, I^2R losses in slot portion of each conductor = $I_z^2 \rho L / a_z$

Thus, heat dissipating surface, S= $(Y_s \times L)$

Loss dissipated per unit area of armature surface, q = loss / surface

$q = (Z_z \times I_z^2 \times \rho \times K) / (a_z \times Y_s \times K)$

or $q = (I_z \times Z_z / Y_s) \times (I_z / a_z) \times \rho = (ac\ \delta\ \rho)$

$$\mathbf{q = (I_z\ xZ_z /Y_s)\ x\ (I_z /a_z)\ x\ \rho\ = (ac\ \ \delta\ \ \rho)}$$

where, $ac = (I_z \times Z_z / Y_s)$ and $\delta = (I_z / a_z)$

So, heat dissipated per unit area of armature surface, q α ac (ampere conductors per metre)

q α specific electrical loading

Temperature rise, $\theta = (Q_c / S) = q \times c = (ac\ \delta\ \rho)\ c$

So,

$$\textbf{specific electrical loading, } ac = (\theta / \rho)\ \delta\ c$$

So, from the above equation, it is clear that the limiting value of specific electrical loading, ac, is fixed by maximum allowable temperature rise θ and the cooling coefficient, c.

1. **Voltage**:

Area of each slot = height of slot x width of slot = $d_s \times w_s$

Total area of all slots = $S \times d_s \times w_s = (\pi D / Y_s) \times d_s \times w_s = \pi \times D \times d_s \times (w_s / Y_s)$

$$\textbf{Total area of conductors in slots} = \pi \times D \times d_s \times (w_s / Y_s) \times S_f$$

where, S_f = space factor for slots.

Also, total area of conductors = $Z \times a_s = Z \times I_z \times \delta = \pi D (ac) / \delta$

$$\textbf{Total area of conductors} = \pi D (ac) / \delta$$

Thus,

$$\textbf{sp. electric loading, } ac = d_s \times (w_s / Y_s) \times S_f \times \delta$$

From the above equation, for a fixed slot width, w_s and slot height d_s and fixed values of current density, δ, the specific electrical loading is dependent upon the space factor, S_f, i.e. the ratio of bare conductor area to total slot area. In high voltage machines, greater insulation thickness is required and thus, the space factor of these machines is lower. Thus there is a reduction of specific electric loading (ac).

1. **Speed of Machines**: If the speed of machine is high, the ventilation of the machine is better and thus greater losses can be dissipated. Thus, a higher value of ac can be used for machine having high speed.

2. **Size of machine**: In large size machines, it is easier to find space for accommodating conductors. In fact, for a given geometry of core, the slot area which can be provided to accommodate the armature windings is proportional to D^2 (square of armature diameter). So, for a given current density, the current is proportional to D^2 and sp. electric loading, ac to D. Thus, greater is the armature diameter of machine, the greater is the value of ac which can be employed in it. But the relationship between ac and D can't kept linear, due to temperature rise increases with increase in diameter, requiring more cooling system to keep down the temperature rise.

3. **Current density**: Thus higher the current density, δ, lower is the value of specific electric loading and vice-versa.

4. **Armature reaction**: If we use a high value of ac, the armature mmf becomes high or armature becomes magnetically stronger. So, under load, there is a distortion on the main field flux due to armature mmf. Thus the cost of conductor used in the machine rises.

Advantages of higher specific electric loading:

a) Size and volume of machine is reduced.

b) Weight of machine is reduced.

c) Overall cost of the machine is reduced.

Disadvantages of higher specific electric loading:

a) Armature copper losses are increased.

b) Commutation becomes inferior.

c) Field copper losses increases due to increased field current.

d) Overall temperature rise increases.

b): Given that, kW= 800kW

V = 400V

N = 300 rpm

P = 10

Commutator diameter = 100 cm

Current density in brushes = 0.075A/mm^2

Brush contact drop = 2.2V

Armature current, I_a = (kW x1000) / V = 2000Amp.

Current per brush arm = Current carried by each brush = 2 I_a /P = 400Amp.

Total brush area per spindle, $A_b = (2 I_a) / (\delta_a \times P) = 5330$ mm^2

Total contact area of all brushes on the commutator, $A_B = p \times A_b = 10 \times 5330$mm^2

$A_B = 53.3 \times 10^{-3}$ m^2

Brush frictional losses, $P_{bf} = \mu P_b p A_b V_c = \mu P_b A_B V_c$

where, μ = coefficient of friction = 0.23

P_b = brush contact pressure on commutator = 14.7 x 10^3 kN /m^2

V_c = peripheral speed of commutator, m/sec.

Thus, $V_c = \pi D n$ = 15.7 m/sec.

So, **Brush frictional losses, $P_{bf} = \mu P_b p A_b V_c = \mu P_b A_B V_c$ = 2830W**

Brush contact losses = I_b x brush contact drop = I_a x brush contact drop = 4400W

Thus,

Total commutator losses = Brush frictional losses + Brush contact losses

Total commutator losses = 7230W

UNIT-II

Q. 3. Determine the main dimensions of the core, the number of turns and the cross-section of conductors for 5kVA, 11000/400V, 50Hz, 1-phase core type distribution transformer. The net conductor area in the window is 0.6 times the net cross section of the core, a flux density of 1 Wb/m^2, current density of 1.4A/mm^2, window space factor 0.2. The height of window is 3 times of width.

Sol:

Given that, net conductor area in window, $A_w K_w$ = 0.6 (net cross section of core) =

0.6 A_i

Thus, $\mathbf{Aw = 0.6A_i / K_w = 0.6\,A_i /0.2 = 3\,A_i}$

For a 1-phase core type transformer, output equation is,

$S = 2.22\, f B_m A_i A_w K_w \delta \times 10^{-3} = 2.22\, f B_m A_i \times 3A_i \times \delta \times 10^{-3}$

By putting all the values given above as,

f = frequency = 50Hz

B_m = maximum flux density = 1Wb/m^2

δ = Current density = 1.4A/mm^2 = 1.4 x 10^6 A/m^2

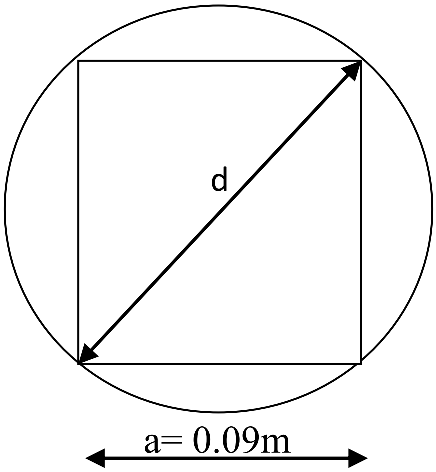
So, $\mathbf{A_i = 0.00732\ m^2}$

Gross cross section of core, $A_{gi} = A_i / K_s = 0.00732/ 0.9 = 0.00814\ m^2$

[where, K_s = stacking factor, 0.9)

In square cross section of core, $Agi = a^2$

So, **width of core, a= 0.09m**



Also, a = 0.71d

Thus, **d = 0.128m**

Window dimensions:

Net gross iron area = $A_{gi} = a^2 = 0.0081m^2$

& Net iron area, $A_i = A_{gi} \times K_s = 0.0081 \times 0.9 = 0.00729\ m^2$

So, **window area,** $\mathbf{A_w = 3\,A_i = 0.02187m^2}$

& window area, $A_w = h_w \times W_w$

where, h_w = height of window and W_w = width of window

Also, given that, $h_w = 3\,W_w$

So, **window dimensions are:** $\mathbf{W_w = 0.085m}$ **and** $\mathbf{h_w = 0.255m}$

Yoke dimensions:

Area of yoke, $Ay = h_y \times D_y$

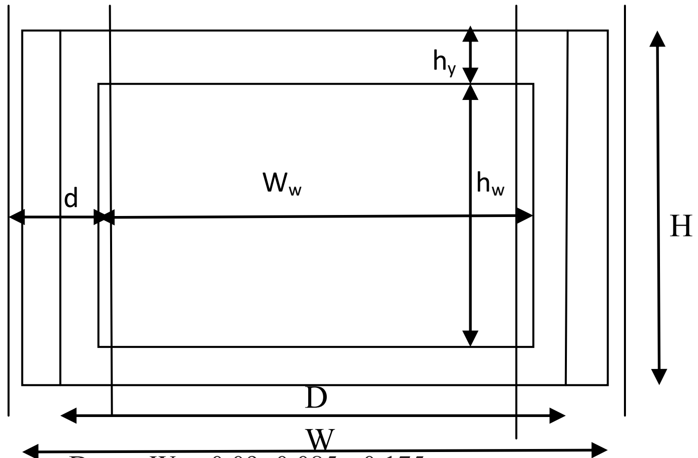
where, h_y = height of yoke and

$\mathbf{D_y}$ **= depth of yoke = width of the largest stamping, a = 0.09m**

& A_y = area of yoke = $A_{gi} = 0.0081m^2$

So, $\mathbf{h_y}$ **= height of yoke = 0.09m**

Overall dimensions:



Distance between the core centres, $D = a + W_w = 0.09+0.085 = 0.175m$

So,

Overall length / width, $W = D + a = 0.265m$

Overall height, $H = h_w + 2\ h_y = 0.435m$

No. of turns and cross-section area of conductors of windings:

As flux, **$\Phi_m = B_m \times A_i = 0.00729$ Wb**

& voltage per turn, **$E_t = 4.44\ f\ \Phi_m = 1.625V$**

So, **no. of primary turns, $N_1 = V_1 / E_t = 6769$**

& **no. of secondary turns, $N_2 = V_2 / E_t = 246$**

Primary winding Current, $I_1 = kVA \times 1000/ V_1 = 0.455A$

So, **area of primary winding conductor, $a_1 = I_1/ \delta = 0.455/ 1.4 = 0.325mm^2$**

Using the circular conductors, diameter of primary winding conductor is,

As, $a_1 = (\pi/ 4)\ d_1^2$

Thus, diameter, **$d_1 = 0.643mm$**

Similarly, Secondary winding Current, $I_2 = kVA \times 1000/ V_2 = 12.5A$

So, **area of secondary winding conductor, $a_2 = I_2/ \delta = 12.5/ 1.4 = 8.93mm^2$**

Using the square conductor of $3 \times 3mm^2$,

area of secondary winding conductor, $a_2 = 9mm^2$

Q. 4. A 2-pole 50Hz, turbo-alternator has a core length of 1.5m. The mean flux density over the pole pitch is 0.5Wb/m^2, the stator ampere conductors per metre are 26000 and the peripheral speed is 100m/sec. The average span of coils is one pole pitch. Determine the output which can be obtained from the machine.

Sol:

Given that, $P = 2$, $f = 50Hz$,

So, speed of the machine, $N_s = 120\ f / P = 3000rpm$

or $n = 3000/60 = 50$ rps.

As peripheral speed, $v = 100m/sec.$

& $v = \pi\ D\ n$

Thus, **diameter of the machine, D = 0.64m**

Assume, K_w =winding factor = 0.955 (**always**)

So, kVA rating, kVA = $C_o D^2 L n = (1.11\pi^2 x K_w x B_{av} x ac x 10^3) D^2 L n$

or, kVA = $(1.11 x \pi^2 x 0.955 x 0.5 x 26000 x 10^3) (0.64)^2 x 1.5 x 50$ = 4178 KVA**MVA rating of the machine = 4.18MVA**

So,

MVA rating of the machine = 4.18MVA

UNIT-III

Q. 5. a). A 3-phase induction motor has 54 stator slots with 8 conductors per slot and 72 rotor slots with 4 conductors per slot. Find the number of stator and rotor turns. Find the voltage across the rotor slip rings when the rotor is open circuited and at rest. Both stator and rotor are star connected and a voltage of 400V is applied across the stator terminals.

b). Discuss how length of air gap is designed in three-phase induction motor.

Sol: a).

Given that, No. of stator slots = 54

No. of stator conductors per slot = 8

Total no. of conductors of stator = 432

& Stator conductor / turns per phase = $Z_{ss} S_s/6$ = 432/ 6 = 72

Similarly, **no. of rotor conductors / turns per phase = $Z_{sr} S_r/6$ = 48**

Voltage applied across stator terminals, V_L = 400 V

So, Stator voltage per phase, Es = 400/ √3 = 231V

Rotor voltage, at standstill, per phase, $E_r = (K_{wr} / K_{ws}) x (T_r/ T_s) x Es = (T_r/ T_s) x Es$

E_r = (48/72) x 231 = 154V (Take $K_{wr} = K_{ws}$)

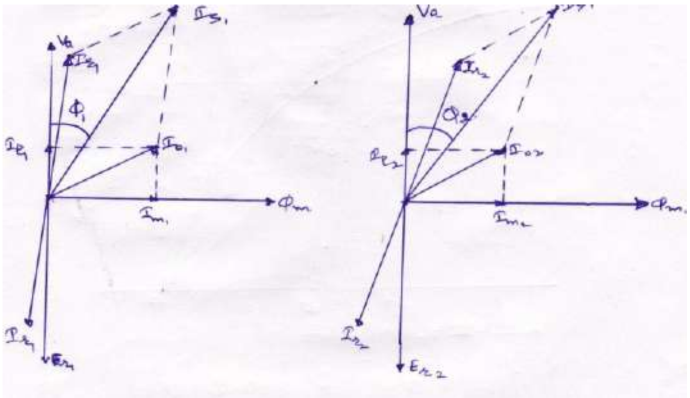
So,

rotor voltage between the slip rings at standstill, $V_r = \sqrt{3} x E_r$ = 266.7V

b). Length of air gap in 3-phase induction motor: The following factors should be considered while estimating the length of air gap:-

1. **Power Factor**: The mmf required to send the flux through the air gap is proportional to the product of flux density and length of air gap. So, it is length of air gap that primarily determined the magnetizing current drawn by the machine, as if the flux densities are low, the mmf required for the air gap is much more than the rest of the magnetic circuit.

Fig. shows the phasor diagrams of an induction motor with two different gap lengths where, V_s = stator applied voltage, Φ_m = air gap flux, E_r = rotor induced emf, I_r = rotor current, I_r' = rotor current referred to the stator side, I_m = magnetizing current, I_L = Loss component of no-load current, I_0 = no-load current, I_s = stator current and Ø = phase angle between stator voltage and stator current.



From the above phasor diagrams, the magnetizing current in case 2 is greater than that of case 1 and thus, the phase angle between the stator voltage and stator current is greater in case 2 i.e. $Ø_2$ is greater than $Ø_1$, or Cos $Ø_2$ is smaller than Cos $Ø_1$. Hence, the power factor of machine with a greater air gap length is smaller.

1. Overload capacity: The over-load capacity of the induction motor is defined as ratio of maximum output to the rated output.

The length of air gap affects the value of total leakage reactance in the case of induction motor. If the length of air gap increases, the total leakage reactance reduces and thus overload capacity increases. So, greater is the length of air gap, greater is the overload capacity.

2. Pulsation Loss: With larger length of air gap, variation of reluctance due to slotting is small and the tooth pulsation losses, due to variation in the reluctance of air gap, is reduced. Hence, the pulsation loss is less with large air gap.

3. Cooling: If length of air gap is large, surface of rotor and stator are separated by a large distance. This would afford better cooling at the gap surfaces.

4. Noise: the principle cause of noise in the induction motor is the variation of reluctance of path of leakage flux. To ensure to reduce the noise, it is necessary to reduce the leakage flux as small as possible. This can be done by increasing the air gap length.

So, it is concluded that the length of air gap in a induction motor should be as small as possible in order to keep magnetizing current small and to improve the power factor.

Calculation of air gap length:

i) For small induction motors, the length of air gap is estimated as,

$$l_g = 0.2 + 2\sqrt{(DL)}, \text{ mm.}$$

ii) Another expression, which can be used for small machines, is

$$l_g = 0.125 + 0.35\,D + L + 0.015\,V_a, \text{ mm}$$

iii) Another formula is,

$$l_g = 0.2 + D, \text{ mm}$$

Q. 6. a). Discuss how various parts of rotor are design in single phase induction motor.

b). Write an expression for calculation of capacitance for maximum torque per ampere in single-phase induction motor.

Sol: a). Design of Rotor:

i) Number of rotor slots: The no. of rotor slots is so chosen that there is no noise producing combinations.

For a smooth running rotor, there will be harmonics fields of stator and rotor slots, with no. of poles differing by less than 4. Harmonic poles due to slots are,

$$\text{Harmonic poles due to slots} = 2(S \pm P/2)$$

The no. of stator slots is usually fixed by winding arrangements, no. of poles etc. The no. of rotor slots must be adjusted to meet the above requirements to give freedom from harmonic poles and best ratio of stator to rotor slots had been selected. The no. of rotor slots should differ from S_s by 20% or more. The no. of slots must also be selected from the point of view of magnetic locking.

ii) Area of rotor bars: The cage rotor may be either of copper bars and end rings or of cast aluminium. With cast aluminium, the manufacturing of machine is cheaper and joints between bars and end rings are eliminated.

Total copper section for main winding of stator, $A_m = 2\,T_m\,a_m$, mm^2

& Total rotor copper section is generally 0.5 to 0.8 of total stator copper section.

Total rotor cross-section of rotor winding, $A_r = S_r \times a_b$

where, a_b = area of each bar, mm^2

S_r = no. of rotor slots.

Ratio of (A_r / A_m) = 0.5 to 0.8 for copper and (A_r / A_m) = 1.0 to 1.6 for aluminium.

iii) Area of End rings:

The rms value of end ring current, $I_e = (S_r \times I_b) / (\pi P)$

Area of each end ring, $a_e = I_e / \delta_e$

Area of each bar, $a_b = I_b / \delta_b$

or, $a_e = (S_r \times I_b) / (\pi P S_e) = (S_r \times a_b \times \delta_b) / (\pi P \delta_e)$ $\mathbf{a_e = (0.32 \times S_r \times a_b / P) \times (\delta_b / \delta_e)}$

iv) Rotor Teeth: The rotor teeth and core densities might be higher in rotor than those of stator because the rotor frequency at normal speed is very low (f' = s f). These densities are chosen slightly higher than the corresponding stator densities.

Flux density in rotor teeth, $B_{tr} = \Phi_m / (S_r / (P \times L_t \times W_{tr}))$

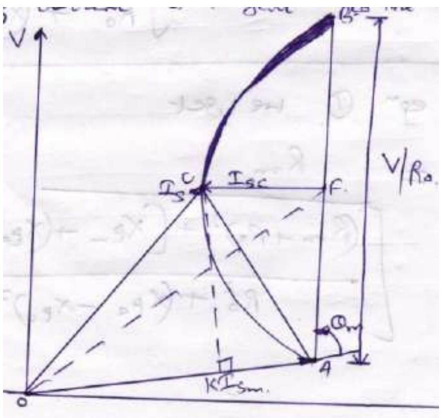
where, W_{tr} = width of rotor teeth.

I) Rotor Core: Flux density in the rotor core is,

Flux density in Core, $B_{cr} = \Phi_m / (2 \times L_i \times d_{cr})$

where, d_{cr} = depth of rotor core.

b). Capacitance for maximum toque per ampere: From the circle diagram of a capacitor start induction motor, the maximum torque per ampere occurs when CK /OC is a maximum, i.e. when the line OC, the line of starting current is tangent to the circle.



Thus from the circle diagram,

$$I_s^2 = (OC)^2 = (OF)^2 - (CF)^2$$

$$= (OF)^2 - (AF)^2 = (OA)^2 + (AF)^2 + 2.\,OA.\,AF.\,\cos\theta_m - (AF)^2$$

$= (OA)^2 + 2.\ OA.\ AF.\ Cos\ \theta_m = (I_{sm})^2 + 2 \times I_{sm} \times (V/2R_a) \times (R_m/Z_m)$

$I_s^2 = (I_{sm})^2 \times [1 + (R_m/R_a)]$

or,

$$R_a = R_m / [(I_s^2/(I_{sm})^2 - 1)]$$

Total stating current, $I_s = I_{sm} [\sqrt{(R_m + R_a)^2 + (X_{lm} + (X_{lc} - X_c)^2} / \sqrt{(R_a^2 + (X_{lc} - X_c)^2)}]$

$$R_a = \frac{R_m}{\dfrac{(R_m + R_a)^2 + (X_{lm} + (X_{lc} - X_c)^2}{(R_a^2 + (X_{lc} - X_c)^2)} - 1}$$

On re-arranging the terns, we get,

$$X_{la} - X_c = \frac{X_{lm} - Z_m \sqrt{(1 + R_m/R_a)}}{(R_m/R_a)}$$

Furthermore,

$$X_{la} - X_c = \frac{X_{lm} - Z_m \times (I_s/I_{sm})}{[(I_s^2/(I_{sm})^2 - 1]}$$

The size of capacitor normally required varies from 20 to 30µF for motors upto 60W and 60 to 100µF for a 90W motor.

UNIT-IV

Q. 7. a). Discuss the advantages of computer aided design

a). Discuss the advantages of computer aided design

b). Discuss the computer aided design technique using synthesis method.

Sol: a).

Advantages of Computer Aided Machine design: The digital computer has completely revolutionized the field of design of electrical machines. The computer aided design eliminates the tedious and time consuming hand calculations. The use of computer makes possible more trial designs. Thus, the advantages of use of a digital computer for the design of electrical machines may be as under:-

1. It has capabilities to store amount of data, count integers, round off results down to integers and refer to tables, graphs and other data in advance.

2. It makes it possible to select an optimized design with a reduction in cost and improvement in performance.

3. A large number of loops can be incorporated in the design programme and thusmakes it easier to compare different designs and best one can be selected.

4. It performs all simple arithmetic operations at a high speed and makes it possible to produce a design at a shorter time.

5. It is capable of automatic operation f design programme.

6. It reduces the probability of errors with highly accurate and reliable results.

7. Larger manufacturing savings can be obtained by optimization of design by use of computers.

8. It is capable of taking logical decisions by itself.

The high rate of performing calculations at reasonable cost and the ability to carry out logical decisions are the most important qualities of the present digital computers. Thus, the digital computers have been responsible for "complete revolution" in the field of electrical machine design.

b). Synthesis Method: The synthesis method is as depicted in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

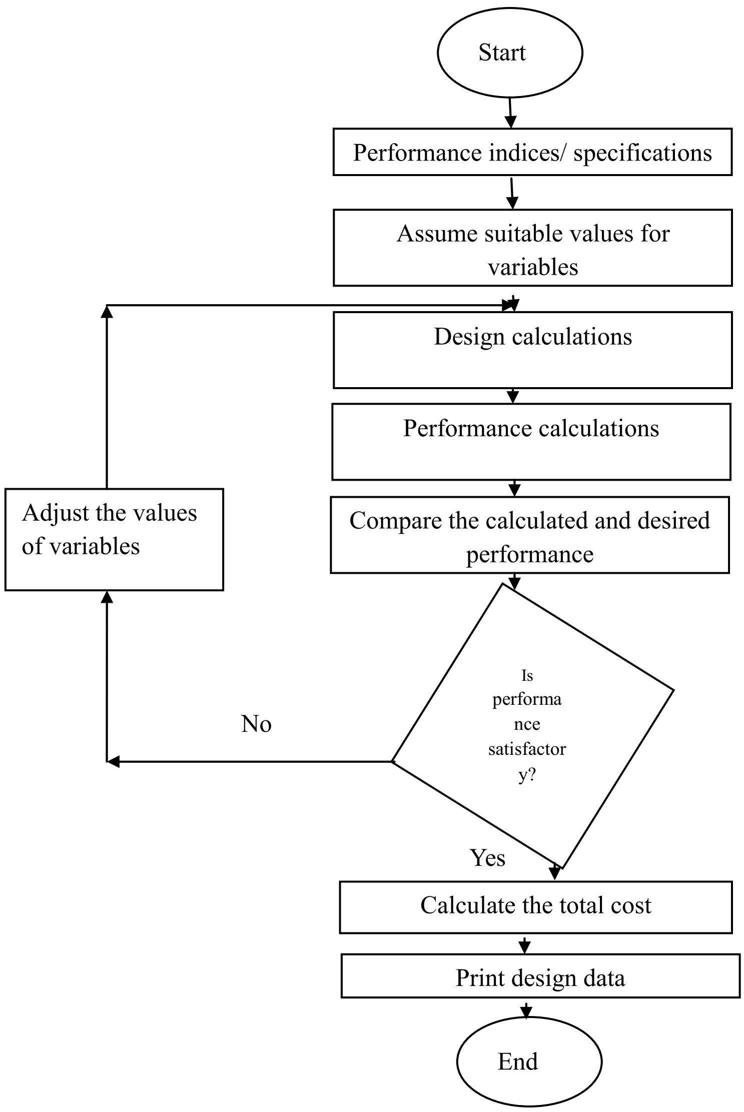
The greatest advantage of synthesis method is as the saving in time in lapsed time and in engineering man hours on account of the decision left to the computer itself.

The synthesis method suffers with a number of serious disadvantages such as:-

1) This method involves too much logic since the logical decisions are left to the computer to take. Now, these logical decisions have to incorporated in the program and before, incorporation, the team of design engineers are to agree upon them.

2) The logical decisions to arrive at a optimum design are too many and then, there are too many people with too many ways to suggest to produce the optimum design and thus, it becomes really hard to formulate a logic for obtaining an optimum

design.



3) The formulation of a synthesis program taking into account of factors listed would make it too complex. So, cost of computer program becomes high and thus use of a large computer and also large running time involves huge expenditure.

4) The synthesis program formulated at a high cost cannot be used for ever, as due to changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions etc., the program has to be changed and up dated keeping. Thus synthesis method requires additional efforts and cost in order for the above.

Q. 8. a). Discuss the general procedure of optimization.

b). Discuss briefly the performance predictions.

Sol: a). General procedure of optimization: The general objective of the optimization is to choose a set of values of the independent variables, subject to various restrictions, which will produce the desired response for the particular problem under examination. A general procedure of optimization is as under:-

1. Define a suitable objective for the problem under examination.

2. Examine the restrictions imposed upon the problem by external agencies.

3. Choose a system or systems for study.

4. Examine the structure of each system and the interrelationship of the system elements and streams.

5. Construct a model for the system. This is a technical design stage which allows the objective to be defined in terms of the system variables.

6. Examine and define the internal restrictions placed on the variables.

7. Carry out the simulation by expressing the objective in terms of the system variables, using the system model. This is the objective function.

8. Analyse the problem and reduce it to its essential features. This reduction is necessary in many cases to allow optimization to carry.

9. Verify that the proposed model represents the system being studied.

10. Determine the optimum solution for the system and discuss the nature of the optimum conditions.

11. Using the information thus obtained, repeat the procedure until a satisfactory result is obtained.

b). Performance predictions: The numerical quantities for which values are to be chosen in producing a design are called “design variables”. The objective function 'Y' is expressed in terms of the independent variables v, where v represents all the variables, $v_1, v_2, \ldots\ldots\ldots\ldots\ldots, v_n$ as

$$Y(v) = Y(v_1, v_2, \ldots\ldots\ldots\ldots\ldots, v_n)$$

subject to in restrictions, generally termed as Constraints, of the form,

$$g_i(v) = 0$$

or $$g_i(v) \leq 0$$

Here, $g_i(v)$ can be variable or a function.

The sole considerations are mathematical and the optimization techniques are determined by the mathematical structures of the objective function and the associated restrictions.

Electrical Machine Design

SOLVED QUESTION PAPER- 4

Note: Attempt Five questions in all, selecting one question from each unit. All question carry equal marks. Assume any missing data if required

UNIT-I

Q. 1: a) What is the output equation of a d.c. machine? Explain clearly. What are the advantages of higher specific electric and magnetic loadings of the d.c. machine?

b) A 250kW, 500V, 600rpm, d.c. generator is built with an armature diameter of 0.75m and a core length of 0.3m. The lap connected armature has 720 0.75m and a core length of 0.3m. The lap connected armature has 720 conductors. Using the data obtained from this machine, determine the armature diameter, core length, number of armature slots, armature conductors and commutator segments for a 350kW, 440V, 720rpm, 6-pole d.c. generator.

Sol: a)

Output equation of DC machines: The output equation of an electrical machine can be expressed in terms of its main dimensions, specific magnetic and electrical loadings and speed, the equation describing this relationship is as output equation.

<u>**DC Machine**</u>:

As power developed by armature in kW,

P_a = generated emf x armature current x 10^{-3}

But, $E = \Phi Z n p / a$

So, $P_a = \Phi Z n p / a \times I_a \times 10^{-3}$

$P_a = (p\Phi)\,[(I_a/a) \times Z]\, n \times 10^{-3}$

$P_a = (p\Phi)\,[I_z \times Z]\, n \times 10^{-3}$

P_a = (total magnetic loading) x (total electrical loading) x n x 10^{-3}

Here, specific magnetic loading, $B_{av} = (p\Phi) / (\pi D L)$ = (Total flux / area of each pole)

So, $\mathbf{p\Phi = B_{av} \times (\pi D L)}$

& specific electric loading, $ac = (I_z \times Z) / (\pi D)$

= total ampere conductor / perimetry of armature

So, $\mathbf{(I_z \times Z) = ac \times (\pi D)}$

Thus, power developed by the armature is, $\mathbf{P_a = C_o . D^2 . L . n}$ $P_a = (1.11\pi^2 B_{av} \times ac \times 10^3)\, D^2 L n$

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

or,

$$\textbf{output coefficient, } \mathbf{C_o = 1.11\pi^2 \times B_{av} \times ac \times 10^3}$$

This is called as output equation of the dc machine.

Advantages of higher specific electric and magnetic loading:

a) Size and volume of machine is reduced.

b) Weight of machine is reduced.

c) Overall cost of the machine is reduced.

Disadvantages of higher specific electric loading:

a) Armature copper losses are increased.

b) Commutation becomes inferior.

c) Field copper losses increases due to increased field current.

d) Overall temperature rise increases.

Disadvantages of higher specific magnetic loading:

a) Iron losses are increased.

b) Field copper losses are increased.

c) High magnitude of no-load current.

d) Tooth flux density increases

e) Noise in the machine increases.

f) Possibility of magnetic saturation in iron parts increases.

Hence, arbitrary increase of specific loading impairs the machine performance and hence there should be a compromise between the selected values of the specific loading. The gap flux density of around 0.45 to 0.5 Tesla is recommended for dc machine upto 10kW while a value of 0.5-0.9Tesla is recommended for dc machines upto 500kW. Gap flux density can be 0.9 to 1.0 9Tesla is recommended for dc machines upto 500kW and upto 10,000kW. Similarly specific electric loading of 12000-15000 ampere conductors per metre is recommended upto the machines upto 5kW while for medium range machines, the range is recommended from 17000-36000 ampere conductors per metre. For range beyond 500kW, specific electric loading could be in the range of 38000-50000 ampere conductors per metre.

b). Given that,

For 250kW Generator,

Power developed by the armature, $P_a = kW / \eta = 250 / (0.91) = 275kW$

(take full load efficiency as 0.91)

Speed, $n = 600 / 60 = 10$ r. p. sec.

So, output coefficient, $C_o = P_a / (D^2 L n) = 275 / [(0.75)^2 x\ 0.3 x\ 10] = 163$

Generated voltage, $E = V_a + I_a x\ r_m = 500 + 0.04 x\ 500 = 520V$

(as assume voltage drop ($I_a r_m$) is 4% of rated voltage)

Now, generated voltage, $E = (\Phi Z n P/ a) = (B_{av} x\ \pi D L/ P) Z n P/ a = \pi x\ B_{av} x\ D L Z n /a$

So, average flux density,

$$B_{av} = (E\ a) / (\pi\ x\ D\ L\ Z\ n) = 0.61 Wb /m^2$$

Now, for 350kW generator,

Power developed by the armature, $P_a = kW / \eta = 350 / (0.91) = 385kW$

(take full load efficiency as 0.91)

Speed, $n = 720 / 60 = 12$ r. p. sec.

So, output coefficient, $C_o = P_a / (D^2 L n) = 163$

(as assuming the data of 250kW generator)

Thus, $\mathbf{(D^2 L) = Pa / (C_o \times n) = 385 / (163 \times 12) = 0.1998\ m^3}$

Assume a square pole face, ratio of pole arc to pole pitch, ψ is 0.66.

So, $\psi = L / \tau$,

or, $L = \psi \times \tau = \psi \times (\pi D / P) = 0.66 \times (\pi D / 6) = 0.345D$

Thus, **length of armature core, L = 0.345D**

Put in above equation of $(D^2 L)$, we get the armature diameter and core length as,

D = 0.835m and L = 0.29m

Flux per pole, $\Phi = B_{av} \times (\pi \times D \times L / P) = 0.61 \times (\pi \times 0.835 \times 0.29/6) = 0.0773$ Wb

Generated voltage, $E = V_a + I_a \times r_m = 440 + 0.04 \times 440 = 457.6V$

(as assume voltage drop $(I_a r_m)$ is 4% of rated voltage)

Number of armature conductors, Z are,

Z = (E a) / (Φ P n) = 493 (As in lap winding, No of parallel paths, a = no. of poles, P)

Number of armature slots:

1. The slot pitch varies from 25 to 35mm. So, the no. of slots varies as (π D/ slot pitch), from $\mathbf{(\pi \times 0.835 / 35 \times 10^{-3}) = 74}$ to $\mathbf{(\pi \times 0.835 / 25 \times 10^{-3}) = 104}$.

2. So, the number of slots should lie between 73 to 96.

Winding: In order that the voltage between adjacent segments should not exceed 15V at no load.

So, minimum number of coils required = E x p /15 = 440 x 6/ 15 = 176

Conductors per slot, Z_s = Z / no. of slots = 493/ 87 = 5.67 (as S = 87)

So, take no. of conductors per slot = 6 and thus, **no. of conductors used, Z = 6 x 87 = 522**

As the minimum no. of coils required = 176,

As assume, diameter of the commutator, $D_c = 0.7$ times armature dia.

Thus, $\mathbf{D_c = 0.7 \times 0.835 = 0.585m}$

Pitch of commutator segments, $\beta_c = (\pi \times D_c) / Z = 7.3mm$

Diameter of commutator, D_c = 0.7 x 0.835 = 0.585m

Pitch of commutator segments, $\beta_c = (\pi \times D_c) / Z = 7.3mm$

Q. 2: a) Derive the condition of the maximum efficiency of a d.c. machine. What do you mean by stray load losses of a d.c. machine?

b) The armature of a 10-pole, 1000kW, 500V, 300rpm d.c. generator has a diameter of 1.6m. There are 450 coils. Determine suitable axial length and diameter of commutator, giving details of brushes, having regard to commutation conditions and temperature rise. The design limitations are:

peripheral speed of commutator > 20m/sec, pitch of segments < 4mm, current/ brush > 70 ampere, temperature rise > 40^{0}C. The other data given is:

The brushes span three segments approximately; brush contact drop = 1.5V, coefficient of friction = 0.15, brush pressure = 20kN/m^2, cooling coefficient = 0.012 / (1+0.1 V_c).

Make suitable assumptions for clearance between brush boxes, staggering of brushes and end play. V_c is the peripheral speed of the commutator.

Sol: a):

Condition of maximum efficiency of a dc generator: The percentage efficiency of a dc generator is given by,

η = (output power) / (output power + losses) = 1- (losses / input power)

In the case of constant speed constant voltage machine, the losses may be divided into three main categories:

a) Constant Losses, P_o: These losses do not vary if the load current varies. For a shunt machine, these losses are: bearing friction and windage losses, brush friction losses, shunt excitation losses and no load iron losses.

b) Losses proportional to armature current, P_1: These losses vary linearly with load current i.e. brush contact loss.

c) Losses proportional to square of armature current, P_2: These losses vary as the square of the armature current and for a shunt machine include: I^2R losses in the armature and stray load losses.

$$\text{Total losses are, } P = P_0 + P_1 + P_2 = k_0 + k_1 \times I + k_2 I^2$$

where, I = total current drawn by the armature of the motor.

& the power input to the motor = V x I

So, the efficiency of dc machine is,

$$\eta = 1 - [(k_0 + k_1 \times I + k_2 I^2) / (V I)]$$

or, $$\eta = 1 - [(K_0 / I + K_1 + K_2 I)]$$

as, $K_0 = k_0 / V$, $K1 = k_1 / V$ and $K2 = k_2 / V$

Thus, in order to find the maximum efficiency, the $d\eta / dI$ is equated to zero.

So, $(K_0 = K_2 I^2$

or, for maximum efficiency, **constant losses = losses proportional to square of current.**

Stray Load Losses: These are certain types of losses which cannot be easily determined. They appear when the machine is loaded. This indeterminable losses are called stray load losses and are due to the following reasons:

I) There is a large increase in the iron losses when the machine is loaded due to distortion of field caused by the armature reaction.

ii) Due to eddy currents in conductors, there is an additional I^2R losses.

iii) When a coil undergoes commutation, it is short-pitched by the brush. This causes a circulating current to flow which produces additional losses.

The stray load losses may be assumed as 0.5% or 1.0% of the basic output of the machine with and without compensating winding respectively. The basic output is that power which corresponds to maximum current at the highest rated voltage for constant speed machines. The basic speed for variable speed machines depends upon the method of speed control.

b): Given that,

speed of the machine = 300 rpm

thus, n = 300/60 = 5 r. p. Sec

The diameter of the commutator is assumed as 0.62 times the armature diameter.

So, diameter of commutator, $D_c = 0.62 \times D = 0.62 \times 1.6 \approx 1.0$m

Diameter of commutator, $D_c \approx 1.0$m

Peripheral speed of the commutator, $V_c = \pi \times D_c \times n = \pi \times 1 \times 5 = 15.7$ m/sec.

(which is less than 20 m/sec as given)

Pitch of the commutator segment, $\beta_c = (\pi \times D_c) / Z = (\pi \times 1.0) / 450 = 7$mm

(as given Z= no. of coils = 450)

(which is not less than 4mm)

So, armature current, $I_a = kW \times 1000 / V = 1000 \times 1000 / 500 = 2000A$

Thus, current per brush arm $= 2\, I_a / P = 2 \times 2000 / 10 = 400A$

As given, current per brush does not exceed to 70A.

Thus, **Minimum no. of brushes required = 400/70 ≈ 6**

Using 8 brushes per brush arm,

Current carried by each brush, $I_b = 400/8 = 50A$.

Area of each brush, $a_b = I_b / \delta_b = 50 / 60 \times 10^{-3} = 0.833 \times 10^{-3}$ mm^2

As given, each brush covers three segments.

So,

Thickness of each brush, $t_b = 3 \times 7 = 21$mm

& Width of each brush, $w_b = a_b / t_b \approx 40$mm

So, Actual area of each brush $= t_b \times w_b = 840$mm^2

& **Total area of brushes per brush arm, $A_b = 8 \times 840 = 6.72 \times 10^{-3}$ m^2**

Length of the commutator, $L_c = n_b (w_b + c_b) + C_1 + C_2$

where, n_b = no. of brushes per brush arm = 8

w_b = width of brush arm = 40mm

c_b = clearance between brushes = 5mm (assumed as standard)

C_1 = clearance allowed for staggering the brushes = 10mm for small machines and 30mm for large machines = 20mm (assumed as standard)

C_2 = clearance for allowing the end play = 10mm to 25mm = 20mm

(assumed as standard)

Thus, length of the commutator, is

Length of commutator, $L_c = 8\,(40+5) + 20 + 20 = 400$mm = 0.4m

Temperature rise:

Brush contact drop = 1.5V

So, brush contact losses $= V \times I_a = 1.5 \times 2000 = 3000W$

Brush frictional losses, $P_{bf} = \mu\, P_b\, p\, A_b\, V_c$

where, μ = coefficient of friction = 0.15

Pb = Brush pressure = 20kN /m^2 = 20 x 10^3 N/m^2

p = no. of poles =10

A_b = Actual area of brush = 6.72 x 10^{-3} m^2

V_c = peripheral speed of commutator = 15.7 m/sec.

Thus, Brush frictional losses, $P_{bf} = \mu P_b p A_b V_c$ = 3165W

So, **Total loss dissipated from the commutator surface = 3000 + 3165 = 6165W**

Cooling coefficient, c = 0.012 / (1+0.1 V_c) = 4.67 x 10^{-3} m^2 - ^{0}C /W

Surface area of commutator, $S_c = \pi$ D L = π x 1.0 x 0.4 = 1.256 m^2

Thus, temperature rise of the commutator, θ is, θ = (total commutator losses x c)/ S_c

$$\theta = (6165 \times 4.67 \times 10^{-3}) / 1.256 = 22.91^0C$$

Temperature rise of the commutator, θ = 22.91^{0}C

UNIT-II

Q. 3: a) A 40Hz transformer is to be used on a 50Hz system. Assuming the steinmetz's coefficient as 1.6 and losses at lower frequency 1.2%, 0.7% and 0.5% for I^2R, hysteresis and eddy current losses respectively. Find

i) losses on 50Hz for the same voltage and current

ii) output at 50Hz for the same total losses as on 40Hz

b) A 250kVA, 6600/400V, 3-phase core type transformer has a total loss of 4800W at full load. The transformer tank is 1.25m in height and 1m x 1.5m in plan. Design a suitable scheme for tubes if the average temperature rise to be limited to 35^{0}C. The diameter of the tubes is 50mm and are spaced 75mm from each other. The average height of tubes is 1.05m, specific heat dissipation due to radiation and convection is respectively 6 and 6.5 W/m^2 - ^{0}C. Assume the convection is improved by 35 percent due to provision of tubes.

Sol: a):

i) For the same voltage and current: As the voltage and current at both 40Hz and 50Hz is same and thus the power output in both the case is also same. Let 40Hz case is as 1 and 50Hz as 2.

As the current is same in both the cases, thus, I^2R losses are same in both cases.

So, $P_{c2} = P_{c1}$ = 1.2%

We have, $E_2/E_1 = (4.44 \times f_2 \times \Phi_{m2} \times T) / (4.44 \times f_1 \times \Phi_{m1} \times T)$

& as, $E_2 = E_1$

So, $\boldsymbol{\Phi_{m2} = \Phi_{m1} \times f_1 / f_2 = \Phi_{m1} \times 40/50 = 0.8\ \Phi_{m1}}$

or, $\mathbf{B_{m2} = 0.8\ B_{m1}}$

Now, as Hysteresis losses $P_h = K_h \times B_m^{\ x} \times f$

or, $P_{h2} / P_{h1} = (K_h \times B_{m2}^{\ x} \times f_2) / (K_h \times B_{m1}^{\ x} \times f_1)$

$= (K_h \times B_{m2}^{\ 1.6} \times f_2) / (K_h \times B_{m1}^{\ 1.6} \times f_1)$

Thus, $P_{h2} / P_{h1} = (0.8)^{1.6} \times 50/40 = 0.875$

or,

$$P_{h2} = 0.875 \text{ x } P_{h1} = 0.875 \text{ x } 0.7 = 0.61\%$$

As, Eddy current losses $P_e = K_e \text{ x } B_m^2 \text{ x } f^2$

or, $P_{e2} / P_{e1} = (K_e \text{ x } B_{m2}^2 \text{ x } f_2^2) / (K_e \text{ x } B_{m1}^2 \text{ x } f_1^2)$

Thus, $P_{e2} / P_{e1} = (0.8)2 \text{ x } (50/40)^2 = 1$

$$P_{e2} = 1 \text{ x } P_{e1} = 1 \text{ x } 0.5 = 0.5\%$$

I) For the same losses at 40Hz: As the power losses at both 40Hz and 50Hz is same and thus the eddy current and hysteresis losses are same but there is change in power output inI^2R losses.

Total losses in 1st case = 1.2 + 0.7 + 0.5 = 2.4%

Total losses in 2nd case = 1.2 + 0.61 + 0.5 = 2.31%

In order that the losses should be equal in both the cases, the I^2R losses have to be increased by 2.4- 2.31 = 0.09% in the 2nd case.

So, **I^2R losses in 2nd case = 1.2 + 0.09 = 1.29%.**

As, I^2R losses in both cases, P_{c2} / P_{c1} = (output in 2nd case / output in 1st case) ^{2}

or, output in 2nd case / output in 1st case = $\sqrt{(P_{c2} / P_{c1})}$

or, output in 2nd case = output in 1st case x $\sqrt{(P_{c2} / P_{c1})}$ = output in 1st case x $\sqrt{(1.29 / 1.2)}$ **Output in 2nd case = 1.038 x output in 1st case**

Thus,

Output in 2nd case = 1.038 x output in 1st case

b): Given that,

kVA= 250 kVA

V_1 = 6600V, V_2 = 440V

Total losses at full load, $Q = P_i + P_c$ =4800W

Transformer tank height, H_t = 1.25m

Transformer tank plan = 1m x 0.5m

Thus,

Surface area of plain tank, S_t = Total area of the vertical sides + one half area of the cover

or, Surface area of plain tank, S_t = 2 (1+0.5) x 1.25 = 3.75 m^2

Let, the area of tubes = xS_t

As given, the surface tank will dissipate heat = (6 + 6.5) S_t = 12.5 S_t W/ ^{0}C

Also given, the loss dissipated by tubes by convection = 1.35 x 6.5 x S_t = 8.8 x S_t W/ ^{0}C

Total loss dissipated by tank walls and tubes = 12.5 S_t + 8.8 x S_t = (12.5 + 8.8 x) S_t W/ ^{0}C

Total area of tank with wall tubes = S_t + x S_t = (1 + x) S_t = (1 + x) 3.75 m^2

Specific heat dissipation = $(P_i + P_c) / (\theta$ x total area) = 4800/ [35 x 3.75 (1 + x)]

or, **Specific heat dissipation = 36.5 ((1 + x) W/ m^2 - ^{0}C**

On comparing the above equations, we get,

(12.5 + 8.8 x) S_t = 36.5 ((1 + x)

or, **x = 2.73**

So, **Area of tubes = x S_t = 2.73 x 3.75 = 10.23 m^2**

&, Wall area of each tube = π x d_t x l_t

where, d_t = diameter of tubes =50mm = 0.05m

l_t = length of tube = 1.05m

Thus, **Wall area of each tube = π x d_t x l_t = π x 0.05 x 1.05 = 0.165m^2**

& Total number of tubes to be provided = Area of tubes / wall area of each tube

Total number of tubes to be provided = 10.23 / 0.165 = 62

All the tubes are spaced by 75m from each other. So, in 1m (1000mm) along the width of tank, 12 tubes can be accommodated (**12 x 75mm**) with 90mm leaving on each side. In 0.5m (500mm) along with depth of tank, 5 tubes can be accommodated (**5 x 75mm)** with 100mm space on each side. Thus, total tubes provided along width and height of the tank are 2 x12 + 2 x 5 = 34, on the first row and the balance 28 tubes can be accommodated on the second row.

Q. 4: a) Show that the output of 3-phase core type transformer is l

Q = 5.23 f B_m H d^2 H_w x 10^{-3} kVA

where f = frequency, B_m = maximum flux density Wb/m^2, d = effective diameter of core m, H = magnetic potential gradient in limb ampere turn/ metre, H_w = height of limb (window), metre.

b) Determine the dimensions of core and yoke of a 200kVA, 50Hz single phase core type transformer. A cruciform core is used with distance between adjacent limbs equal to 1.6 times the width of core laminations. Assume voltage per turn 14V, maximum flux density 1.1WB/m^2, window space factor = 0.32, current density 3amp /mm^2 and stacking factor = 0.9. The net iron area is 0.56 d^2 **in a cruciform core where d is the diameter of circumscribing circle. Also the width of largest stamping is 0.85** d.

Sol: a): As per output equation of 3-phase core type transformer is,

kVA = 3 x E x I x 10^{-3} = 3 x 4.44 x f x Φ_m x T x I x 10^{-3}

In the 3-phase core type transformer, each limb has one primary and one secondary winding wound on it and so, total mmf over one limb = 2 (T x I).

Thus, magnetic potential gradient, H = total mmf / (length of limb)

H = 2 TI / H_w

or, T x I = (H x H_w) / 2

& A_i = (π/4) x d^2

Put all the values in the above equation, we get,

kVA = 3 x 4.44 x f x B_m x A_i x [(H x H_w) / 2] x 10^{-3}

or, kVA = 3 x 4.44 x f x B_m x (π/4) x d^2 x [(H x H_w) / 2] x 10^{-3}

On solving, we get,

kVA = 5.23 f B_m H d^2 H_w x 10^{-3} kVA

b): Given that, for a single phase core type transformer,

kVA = 200kVA

f = 50Hz

Distance between the adjacent limbs, D = 1.6 x width of core lamination (a)

or, D = 1.6 x a

Voltage per turn, E_t = 14V

Maximum flux density, B_m = 1.1Wb/m^2

Current density, δ = 3 A/mm^2 = 3 x 10^6 A/m^2

Stacking factor, K_s = 0.9

Window space factor, K_w = 0.32

Width of largest stampings, a =0.85 d

Net iron area, A_i = 0.56 d^2

Core dimensions:

Voltage per turn, E_t = 4.44 x f x B_m x A_i = 14V

So, **Net iron area, $A_i = E_t / (4.44 \times f \times B_m)$ = 0.0573 m^2**

Net iron area, A_i = 0.56 d^2 = 0.0573

Diameter of circumscribing circle, d = √(0.0573/0.56) = 0.32m

Width of largest stampings, a =0.85 d = 0.85 x 0.32 = 0.272m

Distance between the adjacent limbs, D = 1.6 x width of core lamination (a) = 1.6 x 0.272

or, D = 0.435m

Width of window, W_w= D – d = 0.115m

As for a single-phase core type transformer, output equation is,

$S = 2.22\, f B_m A_i A_w K_w \delta \times 10^{-3}$

Thus, on putting all the values calculated above, we get,

A_w = 0.0293m^2

As, area of window, Aw = height of window h_w x width of window W_w

So, **height of window, $h_w = A_w / W_w$ = 0.26m**

For a cruciform stepped cross-section of the core, we get the dimension of yoke as,

Yoke dimensions:

Depth of Yoke, D_y = width of the largest stamping (a) = 0.272m

Thus, **Dy = 0.272 m.** **& height of yoke, h_y = 0.272m**

Overall dimensions:

Overall width of frame, W = D + a = 0.435 + 0.272 = 0.707m

Overall height of frame, H = h_w + 2 h_y = 0.25 + 2 x 0.272 = 0.794m

UNIT-III

Q. 5: a) What are the advantages of hydrogen cooling of turbo alternators? How do you calculate the quantity of cooling medium to absorb losses of rotating machines?

b) A turbo-alternator runs on test at a continuous rated load of 30MVA with a power factor 0.8. The following

cooling measurements are taken:

Volume of cooling air measured at intake = 30 m^3/sec.

Intake air temperature = 15^{0}C

Outlet air temperature = 45^{0}C

Barometric reading = 750mm of Mercury

i) Find the efficiency of the machine, taking the specific heat of air at constant pressure as 1000J/kg-^{0}C and the volume of 1kg air at 0^{0}C and a pressure of 760mm of mercury at 0.78m^3.

ii) Calculate the amount of cooling water in litre per second to cool the air, assuming the temperature rise to water to be 8^{0}C.

Sol: a): Advantages of Hydrogen cooling of turbo-alternators:

1. **Increased efficiency**: An increase in efficiency results from reduction in the ventilation losses which are a major portion of the total losses in a high speed machine. This is because the density of the hydrogen is only 0.07 times the density of the air and thus the power required to circulate the hydrogen is about 1/4th of power required for circulation of air.

2. **Increase in rating**: Hydrogen heat transfer coefficient 1.5 times and its thermal conductivity us 7 item than that of air. Therefore, the heat generated is more effectively removed and the active materials can be loaded more than is possible with air cooling.

3. **Increase in life**: The life of the machine is mainly the life of the insulating materials and air pockets in insulation can be sources of such high local temperatures that there is always a risk of insulation breakdown and fire. The thermal conductivity of hydrogen is nearly 7 times that of air and is of the same order as the insulation. Thus, when the air pockets are filled with hydrogen, heat conduction through them will be as good as through, winding insulation and high local temperature rise are not there. Further, when the air is used as a coolant in high voltage windings can fall due to destructive action of corona discharge, which forms ozone, nitric acid and other chemical compounds which affects the organic material in the insulation. Whereas when the hydrogen is used as coolant, sufficient air is not present for form a corona discharge. Hence the life of machine is increased.

4. **Elimination of fire hazards**: The outbreak of fire inside the machine is impossible as hydrogen does not support burning.

5. **Smaller size of coolers**: The size of coolers require to cool the gas are smaller in size when hydrogen is used as coolant.

6. **Less Noise**: The noise produced by a hydrogen cooled machine is less as the rotor moves a medium of lesser density.

Quantity of cooling medium: The quantity of cooling medium (coolant) required to absorb losses of machines can be calculated as below:

Let Q = losses to be dissipated, kW

θ_i = inlet temperature of cooling medium. ^{0}C

θ = temperature rise of cooling medium, ^{0}C

H = barometric height of mercury, mm of mercury

P = pressure, N/m^2

a) Air: Heat to be carried away = Q kW = Q x 10^3 W or J/sec

Let c_p = specific heat of air at constant pressure, J/kg – ^{0}C

As, heat = weight x sp. heat x temperature rise

&, heat per second = weight of air Kg/sec x sp. heat in J/kg -^{0}C x temperature rise in ^{0}C

So, Weight of air = $(Q \times 10^3) / (c_p \times \theta)$ kg /sec

Let volume of 1 kg air at N.T.P. (0^0C or 273^0K and 760mm of mercury) = V m^3

So, Volume of air required a N.T.P. = $[(Q \times 10^3) / (c_p \times \theta)] \times V\ m^3$/ sec

Applying kelvin's law, we get, $\mathbf{(P_1 V_1 / T_1) = (P_2 V_2 / T_2)}$

Volume of air under actual working condition is,

$\mathbf{V_a = (Q / c_p \times \theta) \times V \times (\theta_i + 273 / 273) \times (760/ H) \times 10^3\ m^3/sec}$

The specific values of dry air are: $\mathbf{c_p = 0.2375}$ **cal/gm-^{0}C = 0.995 kJ/ kg-^{0}C, V = 0.775 m^3**

Thus, volume of air required as cooling medium is as under:

$$\mathbf{B_{av} = (E\ a) / (\pi \times D\ L\ Z\ n) = 0.61 Wb /m^2}$$

2. Hydrogen: The specific heat of hydrogen at constant pressure is $\mathbf{c_p = 3.4}$ **cal/gm-^{0}C** and volume of 1Kg of dry gas hydrogen is 11.3m^3 at N.T.P. (0^0C or 273^0K and 760mm of mercury).

As per the above procedure, we get volume of hydrogen required to dissipate the heat with a temperature rise of θ^0C,

$$\mathbf{V_h = 0.8\ (Q / \theta) \times (\theta_i + 273 / 273) \times (760/ H)\ m^3/sec}$$

The value of H for hydrogen is 2000-2500mm

3. Water: The specific heat of hydrogen at constant pressure is $\mathbf{c_p = 1}$ **cal/gm-^{0}C = 4.18 kJ/ kg-^{0}C**. The volume of water required to dissipate the heat with a temperature rise of θ^0C,

$$\mathbf{V_w = 1000\ Q / (\theta \times 4.18) = 0.24\ Q/\theta\ litre/sec}$$

4. Oil: The volume of oil required to dissipate the heat of Q kW with a temperature rise of θ^0C,

$$\mathbf{V_w = 0.24\ Q/ (0.35\ to\ 0.5)\theta\ litre/sec}$$

b)

I): Given,

Volume of cooling air measured at intake, $V_a = 30\ m^3$/sec.

Intake air temperature, $\theta_i = 15^0$C

Outlet air temperature, $\theta_o = 45^0$C

Temperature rise, $\theta = \theta_o - \theta_i = 30^0$C

Barometric reading, H = 750mm of Mercury

KVA = 30 x 10^3 kVA

power factor, Cos Ø = 0.8

As per the formula for quantity of air required,

$V_a = 0.78\ (Q / \theta) \times (\theta_i + 273 / 273) \times (760/ H)\ m^3/sec$

or, $30 = 0.78\ (Q/30) \times (15+273 /273) \times (760/750)$

we get, **Q = 1080kWEfficiency, η = output power / (output power + losses) = 95.7 %.**Output power = kVA x p.f. = 30 x 10^3 x 0.8 = 24000 kW

So, **Efficiency, η = output power / (output power + losses) = 95.7 %.**

ii): As losses, Q = 1080 kW

Temperature rise, $\theta = 8^0$C$\mathbf{V_w = 0.24\ Q/\theta}$ **litre/sec = (0.24 x 1080 /8) = 32.4 litre/ sec**

Amount of water required to cool the air in litre/sec. is,

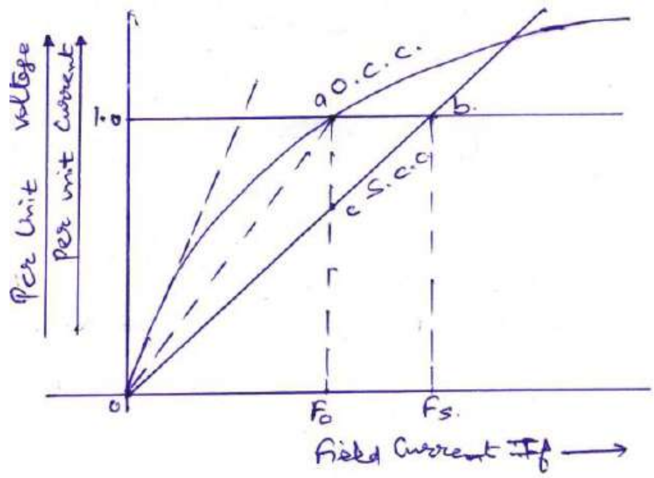
$$V_w = 0.24\ Q/\theta \text{ litre/sec} = (0.24 \times 1080/8) = 32.4 \text{ litre/ sec}$$

Q. 6: a) Explain the effect of short circuit ratio on the performance of synchronous machine.

b) Determine a suitable number of slots and conductors per slot for the stator winding of a 3-phase, 3300V, 50Hz, 300rpm alternator. The diameter is 2.3m and the axial length of the core is 0.35m. The maximum flux density in the air gap should be approximately 0.9Wb/m^2. Assume sinusoidal flux distribution. Use single layer winding and star connection for stator.

Sol: a): The short-circuit ratio (SCR) of a synchronous machine is defined as the ration of field current required to produce rated voltage on open-circuited to field current required to circulate the rate current at short-circuit.

$$\text{SCR} = \frac{\text{Field current for rated voltage at O.C.C.}}{\text{Field Current for rated current at S.C.C.}}$$



O.C.C and S.C.C.

SCR = OFo / OFs = c Fo / b Fs = c Fo / a Fs = 1/ (a Fs / c Fo)

or, **SCR = 1/ (per unit voltage on open circuit / per unit current on short circuit)**

or, **SCR = 1/Xd**

Thus, the short-circuit ratio (SCR) is the reciprocal of synchronous reactance, X_d. For modern turbo-alternators, the SCR is normally between 0.5 to 0.7. For salient pole hydroelectric generators, SCR varies from 1.0 to 1.5.

Effect of short circuit ratio (SCR) on machine performance:

i) Voltage regulation: a low value of SCR means that the synchronous reactance is of higher value. Synchronous machines with low value of SCR have greater changes in voltage under fluctuations of load i.e. the voltage regulation is poor.

ii) Stability: A machine with low value of SCR has a lower stability limit as the maximum power output of the machine is inversely proportional to X_d.

iii) Parallel operation: Machines with a low value of SCR are also difficult to operate in parallel because a high value of X_d gives a small value of synchronising power. This power is responsible for keeping the machines in synchronism. So, the parallel operation of the machine with high value of X_d becomes very difficult if they are interconnected with transmission lines.

iv) Short Circuit current: A small value of SCR indicates a smaller value of current under short circuit conditions owing to large value of X_d.

v) Self excitation: Machine feeding long transmission lines should not be designated with a small SCR or high X_d, as this would lead to large voltages on open circuit produced by self excitation, thus large capacitive currents will be drawn by the lines.

Thus, a machine with large value of SCR has a higher stability and low value of voltage regulation. On the other hand, a large value of SCR has a high value of short circuit current. Thus with a large value of SCR, the machine has long air gap which means that the mmf required by field is large. Hence the machine with large SCR is costlier to build. But in present day, all the machines are designed with low SCR, but to presence of better active control and excitation systems.

b): Given that,

Synchronous speed, N_s = 300rpm or 5 r. p. sec.

f = 50 Hz

Thus, no. of poles P = (120 f /N_s) = 20

Voltage, V =3300V

Diameter of armature, D =2.3m

Length of armature, L = 0.35m

Max. flux density, B_m = 0.9 Wb/m^2

So, average flux density, B_{av} = (2/π) x B_m = 0.574 Wb/m^2

Thus, **flux per pole, Φ = B_{av} x (π D L/ P) = 0.574 x (π x 2.3 x 0.35 /20) = 0.0725Wb**

Voltage per phase, E_{ph} = V / √3 = 1905V

&, Turns per phase, Tph = E_{ph} / (4.44 x f x Φ x K_w) = 124 (Take K_w = 0.955)

As per assumption, the length required for transpose a strand from one to another strand (**slot pitch, Y_s**) for 3.3kV machines is normally taken as 40mm.

No. of slots per pole per phase, q = No. of slots/ (no. of phases, m x no. of poles, P)

or, q = (π D/Y_s) / [m x P) = (π x 2.3/0.04) / (3 x 20) = 3

For a single layer winding,

Total no. of slots of stator, S = 3 x p x q = 180

Total no. of stator conductors, Z = 6 x T_{ph} = 6 x 124 = 744

Conductors per slot, Z_s = 744/180 = 4

Total no. of conductors, Z = 4 x 180 = 720

Total no. of slots of stator, S = 3 x p x q = 180

Conductors per slot, Z_s = 744/180 = 4

Turns per phase used, T_{ph} = Z/ 6 = 720/6 = 120

UNIT-IV

Q. 7: a) Determine the main dimensions, number of radial ventilating ducts, number of stator slots and the number of turns per phase of a 3.7kW, 400V, 3-phase, 4-pole, 50Hz squirrel cage induction motor to be started by a star-delta starter. Work out the winding details. Assume:

Average flux density in the gap = 0.45 Wb/m^2, ampere conductors per metre = 23000, efficiency = 0.85 and power factor 0.84.

Machines rated at 3.7kW, 4-pole are sold at a competitive price and therefore, choose the main dimensions at a cheap design.

b) What do you mean by carter's air gap coefficient for 3-phase induction motor? Explain clearly.

Sol: a): Given that, for a 3-phase squirrel cage induction motor

kW= 3.7kW

V =400V

No. of poles P = 4

f = 50Hz

efficiency, $\eta = 0.85$

power factor, Cos Ø 0.84.

Average flux density in the gap, $B_{av} = 0.45$ Wb/m^2,

Ampere conductors per metre, ac = 23000 AT/m,

Assume, winding factor, $K_{ws} = 0.955$, stacking factor, $K_s = 0.9$

Main dimensions:

kVA input, Q = kW / (η x Cos Ø) = 5.18kVA

Output coefficient, $C_o = 11 \times \pi^2 \times B_{av} \times ac \times 10^3 = 11 \times \pi^2 \times (0.45) \times 23000 \times 10^3 = 108.7$

Synchronous speed, ns = 2 f / P = 2 x 50 /4 = 25 r. p. sec.

Thus, product, $D^2 L = kVA / (C_o \times n_s) = 1.91 \times 10^{-3}$ m^3

Assume, as for a cheap design, L / τ = 1.5 to 2. So, take L/ τ = 1.5.

So, we have, L / (π D /P) = 1.5

or, L /D = 1.5 x π / P = 1.178

Put this ratio in product, we get the dimensions as,

D = 0.117m & L = 0.13m

Pole pitch, $\tau = \pi D / P = 0.094$m

As per assumptions, if the stator is provided with radial ventilating ducts if the core length exceeds 100 to 125mm or above, the duct width is about 8mm to 10mm.

So, in this case, length of iron core is 0.13m (130mm), then the radial ventilating duct is 10mm (0.01m) wide.

Thus, **net iron length, $L_i = \tau$ (0.13 - 0.01) = 0.094 (0.13 – 0.01) = 0.108m.**

Turns per phase:

Flux per pole, $\Phi = B_{av} \times (\pi D L / P) = 0.45 \times (\pi \times 2.3 \times 0.13/ 4) = 5.28 \times 10^{-3}$ Wb.

As the machine is started with star-delta starter, thus the machine is used for delta connection.

So, stator voltage per phase, $E_{ph} = 400V$

Thus, **Stator turns per phase, $T_{ph} = E_{ph} / (4.44 \times f \times \Phi \times K_{ws}) = 343$**

Number of stator slots: In general, the number of slots should be selected to give an integral number of slots per pole per phase. For semi-closed slots, the slot pitch may be less than 15mm. Thus for this type of small rating machine, semi-closed slots are preferred.

Thus, as per assumption, no. of slots per pole per phase, q = 3.

Total no. of stator slots, $S_s = q \times m \times P = 3 \times 3 \times 4 = 36$

So,

Stator slot pitch, $Y_s = \pi D / S_s = \pi \times 0.117 / 36 = 0.01021m = 10.21mm$

Total no. of stator conductors, $Z = 6 \times T_{ph} = 6 \times 343 = 2058$

Conductors per slot, $Z_s = Z / S_s = 2058 / 36 = 57$

Winding details: For small machines of this type, a single layer mush winding placed in semi-closed slots is used. So,

Number of coil = Z / 2 = 18

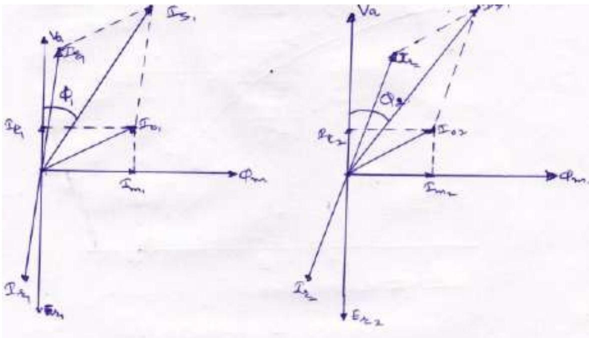
& Number of coils per phase = 18 / 3 = 6

As there are no. of slots per pole per phase, q = 3, then coil pitch (no. of slots per pole) is 9 slots. So, the coil side in slot 1 is connected to coil side in slot 10.

b): Length of air gap in 3-phase induction motor: The following factors should be considered while estimating the length of air gap:-

1. **Power Factor**: The mmf required to send the flux through the air gap is proportional to the product of flux density and length of air gap. So, it is length of air gap that primarily determined the magnetizing current drawn by the machine, as if the flux densities are low, the mmf required for the air gap is much more than the rest of the magnetic circuit.

Fig. shows the phasor diagrams of an induction motor with two different gap lengths where, V_s = stator applied voltage, Φ_m = air gap flux, E_r = rotor induced emf, I_r = rotor current, I_r' = rotor current referred to the stator side, I_m = magnetizing current, I_L = Loss component of no-load current, I_0 = no-load current, I_s = stator current and Ø = phase angle between stator voltage and stator current.



From the above phasor diagrams, the magnetizing current in case 2 is greater than that of case 1 and thus, the phase angle between the stator voltage and stator current is greater in case 2 i.e. $Ø_2$ is greater than $Ø_1$, or Cos $Ø_2$ is smaller than Cos $Ø_1$. Hence, the power factor of machine with a greater air gap length is smaller.

2. **Overload capacity**: The over-load capacity of the induction motor is defined as ratio of maximum output to the rated output.

The length of air gap affects the value of total leakage reactance in the case of induction motor. If the length of air gap increases, the total leakage reactance reduces and thus overload capacity increases. So, greater is the length of air gap, greater is the overload capacity.

1. Pulsation Loss: With larger length of air gap, variation of reluctance due to slotting is small and the tooth pulsation losses, due to variation in the reluctance of air gap, is reduced. Hence, the pulsation loss is less with large air gap.

2. Cooling: If length of air gap is large, surface of rotor and stator are separated by a large distance. This would afford better cooling at the gap surfaces.

3. Noise: the principle cause of noise in the induction motor is the variation of reluctance of path of leakage flux. To ensure to reduce the noise, it is necessary to reduce the leakage flux as small as possible. This can be done by increasing the air gap length.

So, it is concluded that the length of air gap in a induction motor should be as small as possible in order to keep magnetizing current small and to improve the power factor.

Calculation of air gap length:

i) For small induction motors, the length of air gap is estimated as,

$$l_g = 0.2 + 2 \sqrt{(DL)}, \text{ mm.}$$

ii) Another expression, which can be used for small machines, is

$$l_g = 0.125 + 0.35 D + L + 0.015 V_a, \text{ mm}$$

iii) Another formula is,

$l_g = 0.2 + D$, mm

Q. 8: a) A 3-phase, 4-pole 50 Hz induction motor has 24 stator slots and 28 rotor slots. Prove that it has tendency to run as a synchronous motor at 214.3rpm.

b) A 11kW, 3-phase, 6-pole, 50 Hz, 220V, star connected induction motor has 54 stator slots, each containing 9 conductors. Calculate the values of bar and end rings current. The number of rotor bars is 64. The machine has an efficiency of 0.86 and a power factor of 0.85. The rotor mmf may be assumed as 85 percent of stator mmf. Also find the bar and end ring sections if the current density is 5 A/mm^2.

Sol: a): Given that for 3-phase induction motor with 4-pole and 50Hz

Synchronous speed, $n_s = 2 f / P = 2 \times 50 / 4 = 25$ r. p. sec.

Thus,

The stator produces the harmonics (due to slotting) is of order, $n = 2 (S_s / P) \pm 1$

& these harmonics revolve at a speed of 1/n of synchronous speed with respect to stator.

So,

The order of forward rotating field produced by stator slotting, $n = 2 (S_s / P) + 1$

$$n = 2 (24 / 4) + 1 = 13$$

& the harmonic field revolve at a speed of $n_s / 13$ with respect to stator

Order of backward rotating field produced by rotor slotting, $n' = 2 (S_s / P) - 1$

$$n' = 2 (28 / 4) - 1 = 13$$

Its speed with respect to the rotor is $-(n_s - n_r) / 13$. The speed of rotor revolves at a speed of 1/13 of the $-(n_s - n_r) / 13 + n_r$ with respect to stator.

Thus, we have both the fields revolving synchronously with respect to each other.

$n_s / 13 = n_r - (n_s - n_r) / 13$

So, **speed of the rotor, $n_r = n_s / 7 = 25/7 \times 60 = 214.3$ rpm**

Therefore, the motor has a tendency to crawl at 214.3 rpm due to harmonic synchronous torque.

b): Given that, for a 3-phase induction motor

Output kW = 11kW

V = 220V

No. of poles P = 6

f = 50Hz

efficiency, $\eta = 0.86$

power factor, Cos Ø = 0.85.

No. of stator slots = 54

No. of conductors per slot = 9

No. of rotor slots = 64

Assume, winding factor, $K_{ws} = 0.955$, stacking factor, $K_s = 0.9$

Stator current per phase, $I_s = kW \times 1000 / (\sqrt{3} \times Vph \times \eta \times \text{Cos } Ø)$

$$\mathbf{I_s = 40A}$$

As per the above information, we get,

No. of stator conductors = 54 x 9 = 486

No. of turns per phase, $T_{ph} = Z / 6 = 486 / 6 = 81$

Stator mmf per phase = 3 x I_{sph} x T_{sph} = 3 x 40 x 81 = 9720 A

As given, **rotor mmf per phase = 85% x (stator mmf) = 0.85 x (9720) = 8250A**

But, rotor mmf = $S_r I_b / 2$

where, S_r = No. of rotor slots

I_b = Rotor bar currents

So, rotor mmf = $S_r I_b / 2 = 8250$

or, $\mathbf{I_b = 258A}$

End ring Current, $I_e = (S_r \times I_b) / (\pi \times p) = 883A$

$\mathbf{I_e = 883A}$

Area of bar section, $a_b = I_b / \delta_b = 258 / 5 = 51.6\ mm^2$

Area of end ring section, $a_e = I_e / \delta_e = 883 / 5 = 176.6\ mm^2$

$\mathbf{a_b = 51.6\ mm^2}$

$\mathbf{a_e = 176.6\ mm^2}$

Electrical Machine Design

SOLVED QUESTION PAPER-5

Note: Attempt Five questions in all, selecting one question from each unit. All question carry equal marks.

UNIT-I

Q. 1: Two DC shunt generators, each with an armature resistance of 0.05 ohms having no load emfs of 250V and 245V, field resistances of 50 and 40 ohms respectively. They are in parallel and supply a total load of 60kW. How do they share the total load?

Sol: Given that, two DC generators are connected in parallel.

No load emf of DC generator, 1 = V_1 = 250V

No load emf of DC generator, 2 = V_2 = 245V

Armature resistance of DC generator, R_a = 0.05Ω

Field resistance of DC generator, 1, R_{sh1} = 50Ω

Field resistance of DC generator, 2, R_{sh2} = 40Ω

Total load shared by the DC generator, P = 60kW

So, armature current of DC generator, 1, $I_{a1} = V_1/R_a = 5000A$

& field current of DC generator, 1, $I_{sh1} = V_1/R_{sh1} = 5A$

Thus, in case of DC shunt generator,

Total line current of DC generator, 1, $I_{L1} = I_{a1} + I_{sh1} = 5005A$

Similarly, armature current of DC generator, 2, $I_{a2} = V_2/R_a = 4900A$

& field current of DC generator, 2, $I_{sh2} = V_2/R_{sh2} = 6.125A$

Thus, in case of DC shunt generator,

Total line current of DC generator, 2, $I_{L2} = I_{a2} + I_{sh2} = 4906.125A$

Thus, Total load current of both generators connected in parallel,

$$I_L = I_{L1} + I_{L2} = 9911.125A$$

Thus, total load shared by the DC generator, 1, $P_1 = (I_{L2} / I_L) \times P$

$$P_1 = (4906.125 / 9911.125) \times 60 = 29.7A$$

& total load shared by the DC generator, 2, $P_2 = (I_{L1} / I_L) \times P$

$$P_2 = (5005 / 9911.125) \times 60 = 30.3A$$

Load shared by the DC generator, 1, P_1 = 29.7A
Load shared by the DC generator, 2, P_2 = 30.3A

Q. 2: Explain the following:

a) General features and limitations of electrical machine design.

b) Design of slots, field poles and commutator in DC machines.

Sol:

a) General features of electrical machine design: Design may be defined as a creative physical realization of theoretical concepts. Engineering design is application of science, technology and innovation to produce machines to perform specified tasks with optimum economy and efficiency.

The problem of design and manufacture is to build, as economically as possible, a machine which fulfils a certain set of specifications and guarantees. Thus, the major considerations to evolve a major design are:

1. Cost, 2. Durability, 3. Compliance with performance criteria as laid down in specifications.

A good design is one where is the machine has reasonable operating life and has a low initial cost. A design process is not merely engineering calculations bur involves careful consideration of the followings.

1. Design base: Matching the existing experience with Research and Development, bringing in the latest material technology, convenience in production line and transportation, working safely and reliability, maintenance and repair, environmental conditions, cost economy, optimization.

2. Specifications: Meeting with customer's requirements, guarantees, satisfy the national and international standards.

3. Design Transfer: Transfer of design to factory foremen, i.e. drawings, processes, instructions, job-flow, meeting with delivery schedule.

4. Information updating: Technical journals, R & D papers and reports, interaction in meetings and seminars.

Knowing the characteristics and specifications that a machine has to satisfy, the main areas of design are:-

a. The magnetic circuits: core yoke and air gap.

b. The electric circuit- windings

c. The insulation.

d. Heating and cooling circuits.

e. The mechanical constructions.

Moreover economy in manufacturing costs, operating and running costs of the machine is also kept in view.

Limitations in electrical machine design: Apart from availability of suitable materials, facilities available for manufacture of required machine parts and facilities required for transportation, the following considerations impose the limitations in design:

a. Saturation of magnetic parts: Electromagnetic machines use ferro-magnetic materials. The maximum allowable flux density to be used is determined by the saturation level of the ferro-magnetic material used. Thus, this leads to higher core losses and increased excitations.

b. Temperature rise: The most vulnerable part of the machine is insulation. The operating life of the machine depends upon the type of insulating materials used in the construction of the machine and life of insulating materials in turns depends upon the temperature rise of the material. Thus, increase in temperature rise, deteriorates the insulation and affects the life of the machine.

c. Insulation: The insulation materials used in a machine should be able to withstand the electrical, mechanical and thermal stresses which are produced in the machine due to high voltage gradient and under short-circuit conditions. Thus the insulation breakdown due to electrical and thermal breakdown considerations.

d. Efficiency: The efficiency of the machines should be as high as possible to reduce the operating cost. Thus, it requires the use of large amount of material, both iron and copper. So, the capital cost of the machine designed with high efficiency is high.

e. Mechanical parts: The construction of an electrical machine has to satisfy numerous technological requirements. The construction should be as simple as possible and also it should be good. Thus, the design of mechanical parts is particularly important in the case of high speed and large size machines. In induction motors, the length of air gap is as small as mechanically possible in order to have a high power factor. The length of air gap and also that of the size of the shaft are mainly decided by the mechanical considerations. The size of the shaft should be such that it does not give rise to excessive magnetic pull when deflected.

f. Commutation: The problem of commutation is important in the use of dc machines. Thus due to commutation, the output power of machine is limited.

g. Power factor: Poor power factor results in larges values of current per phase for the same power and thus, larger conductor size have to be used. As in case of induction motors, the size and hence cost of machines can be reduced by using a high value of flux density in the air gap but this makes the saturation of iron parts and thus a poor power factor. So, the value of flux density used depends upon the power factor and hence power factor becomes a limiting factor.

h. Customer's specifications: The limitations imposed by the customer's specifications on the design of machines are obvious, as due to economic constraints and specifications as laid down in the customer's orders.

I. Standard specifications: These specifications are the biggest strain on the design because both the manufacturer and the customer cannot get away from them without satisfying them.

UNIT-II

Q. 3: A 11/0.4 kV star-delta transformer is connected to 3-phase balanced load of 300kVA at unity power factor and also to a single phase load of 60kVA at unity power factor. Calculate the values of current on the primary side. The no-load current and the internal leakage impedance drops are neglected.

Sol: Given that,

line voltage on primary side, $V_{1L} = 11kV$

line voltage on secondary side, $V_{2L} = 0.4kV = 400V$

So, phase voltage on primary side, $V_{1p} = 11 / \sqrt{3} = 6.35kV$

Phase voltage on secondary side, $V_{2p} = 0.4kV = 400V$

& **transformation ratio, $K = V_{2p} / V_{1p} = 0.063$**

Load connected to secondary side of transformer, 3-phase, 300kVA at Cos Ø = 1

Thus, **load current in this load, $I_{L1} = 300 / (\sqrt{3} \times 0.4) = 273.86A$**

Load connected to secondary side of transformer, 1-phase, 60kVA at Cos Ø = 1

So, load current in this load, $I_{L2} = 60 / 0.4 = 150A$

Total secondary winding current in the load, $I_2 = I_{L1} + I_{L2} = 423.86A$

Thus, total current on primary side, $I_1 = K \times I_2 = 0.063 \times 423.86 = 26.7A$

Total current on primary side, $I_1 = 26.7A$

Q. 4: Two three-phase 45MVA star-connected alternators each have a sub-transient reactance of 0.73 ohms per phase. Calculate the synchronizing current at the time of closing of synchronising switch when with the emfs are equal to 11kV but are displaced from each other by 30^0.

Sol: Given that, line voltage of star connected alternators = 11kV

So, voltage / phase, = $11000 / \sqrt{3} = 6351V$

Full load current, $I = KVA/V_{ph} = 45 \times 10^3 / \sqrt{3} \times 11 = 2362A$

Already given, $X_s = 0.73$ ohm per phase

& $\alpha = 30^0 = 30^0 \times \pi / 180) = (\pi / 6)$ electrical radian.

So,

Value of synchronizing current, $I_{sy} = E_r$ / (syn. Impedance, X_s)

or, $\mathbf{I_{sy} = (\alpha \times E) / (2 \times X_s)}$

or, $I_{sy} = [(\pi / 6) \times 6351] / (2 \times 0.73) = 2278A$

Synchronizing current, I_{sy} = 2278A

UNIT-III

Q. 5: A 400V, 4-pole, 50Hz, 3-phase squirrel cage induction motor develops full load torque at 1470 rpm and has full load power factor of 0.85. Its magnetising and rotational losses may be neglected. If the supply voltage reduces to 340V, with the load toque remaining constant, obtain the motor full load power factor.

Sol: Given that, No. of poles, P = 4,

Frequency, f = 50Hz

So, synchronous speed, $N_s = 120 f / P = 1500$rpm

Given, Speed of rotor, N = 1470rpm

So, Full load slip, $s_{fl} = (N_s - N) / N_s = (1500 - 1470) / 1500 = 0.02$

Also given, Input voltage, $V_1 = 400V$

& Voltage, $V_2 = 340V$

Now, as Full load torque, $T = (k \Phi s E_2^2 R_2) / [R_2^2 + (sX_2)^2]$

or, $T = (k \Phi s V^2 R_2) / [R_2^2 + (sX_2)^2]$ $\quad$ **($E_2 \alpha \Phi \alpha V$)**

Since the torques are same in both the cases i.e. $T_2 = T_1$

For torque – speed characteristics of motor under load, the parameters under two different load conditions are related by equation.

$$\mathbf{s_2 = s_1 \times (T_2 / T_1) \times (R_2 / R_1) \times (V_1 / V_2)^2}$$

or, $\mathbf{s_2 = (0.02) \times (R_2/ R_1) \times (400 /340)^2 = 0.027 (R_2/R_1)}$

Also given that, full load power factor, $\cos Ø_1 = 0.85$

or, $Ø_1 = \cos^{-1} (0.85) = 31.78^0 = s_1 X_1 /R_1 = 0.02 X_1 /R_1$

or, $\mathbf{X_1 / R_1 = 0.636}$

$\tan Ø_2 = s_2 x X_2 /R_2 = 0.027 (R_2/R_1) \times X_2 / R_2 = 0.027 \times (X_2 / R_1)$

or, $\tan Ø_2 = 0.027 \times 31.78^0 \times 0.02 = 0.0172$

or, $\mathbf{Ø_2 = \tan^{-1} (0.0172) = 0.983^0}$

So, at reduced voltage, full load power factor, $\cos Ø_2$ is,

$$\mathbf{\cos Ø_2 = \cos (0.983) = 0.9998 \approx 1}$$

Q. 6: Give a detailed comparison of single phase and three-phase induction motors.

Sol: Comparison between single-phase and three-phase induction motors:

Three-phase induction motor	Single-phase induction motor
1. These machines are used for very high power ranges from few kW to several hundreds of kW.	1. These machines are adopted for small power applications, especially in fractional kilowatt range, from a fraction of kilowatt to about 3.7kW.
2. These machines are either squirrel cage rotor type or wound rotor type construction.	2. These motors are always having a squirrel cage type rotor construction.
3. These machines have no special theory required for its operation.	3. These machines work on the theory of double field revolving theory.
4. Efficiency is very high about 95-98%.	4. Efficiency is only about 50% of that of 3-phase motor, for a given frame size and temperature rise.
5. These machines are used in high-power drives requiring constant as well as variable speed drives,	5. These machines are used in low power drives, requiring constant speed.
6. These machines have a very high power factor ranging from 0.85 to 0.95.	6. These machines have a very low power factor.
7. These machines are inherently self starting in nature. Thus, these have a wide variety of industrial and commercial applications.	7. These machines are not self starting, therefore, some methods are advisable to make them self starting, consisting of two windings- 1) the main winding in the direct axis to carry most of the current and 2) the auxiliary winding in the quadrature axis with a different number of turns to generate the starting torque.
8. These machines are less costly.	8. Due to the above facts, these machines are more costly.
9. These machines are more robust.	9. These machines are less robust.
10. These have a wide variety of industrial and commercial applications.	10. These machines have a wide use in industry apparatus such as machine tools, domestic apparatus and agricultural machinery. Some of the applications are fans, refrigerators, mixers, vacuum cleaners, washing machines, other kitchen equipments, small farming appliances etc.

UNIT-IV

Q. 7: Apply computer aided design for designing transformers. Explain all the steps involved and give design algorithms.

Sol: Computer aided design for designing transformers: The transformer is a

static device which transfers the electrical energy from one or more primary windings to one or more secondary windings using the law of electro-magnetic induction using the magnetic circuit. Class of transformers (power or distribution), type of construction (core or shell type), kVA ratings, voltage level, type of connections, percentage of impedances and tappings, temperature rise are the basic requirements of customer's specifications.

To achieve the better performance, the whole design procedure is divided into several parts as follows:-

i) Core design

ii) Window dimension design

iii) Yoke design

iv) Overall design

v) Low voltage winding design

vi) High voltage winding design

vii) Resistance calculation.

viii) Leakage reactance calculation.

ix) Loss calculation.

x) Efficiency calculation.

xi) No-load current calculation.

1. Core design: Core design is dealt with the type of core (core or shell) of the transformer. The value of 'K' is constant depending upon the type of transformer (power or distribution). The allowable flux density in the core lies between 1.0 to 1.35Wb /m^2 for distribution transformer and between 1.25 to 1.45 Wb/m^2 for power transformers. The core section of the core type transformer can be

a. Square.

b. Cruciform or 2-stepped

c. 3-stepped

d. 4-stepped

2. Window dimensions: Flux density in the window section of the transformer is same as that of the core of the transformer. For large power transformers upto 50kVA self cooled, current density, δ, usually lies between 1.1 to 2.3 A/mm^2, for large power transformers self-oil cooled or air blast type, δ = 2.2 to 3.2 A/mm^2 and for large power transformers with forced circulation of oil or water cooled transformers, δ = 5.4 to 6.3 A/mm^2.

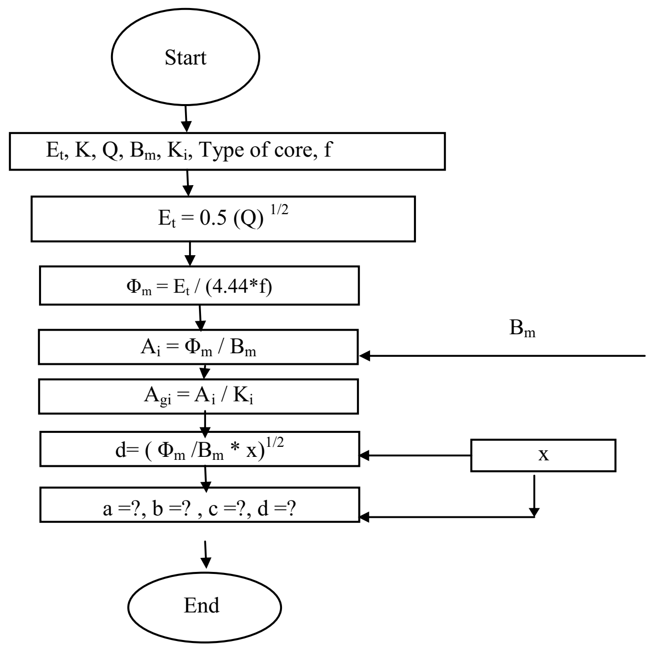
3. Yoke design: Area of the yoke is taken as 15 to 25 percent larger than that of the core of the transformer. The section of the yoke is either rectangle or square. For rectangular yoke, the yoke highest side of the laminated core (width of the largest stamping) is taken as depth core.

4. Low voltage winding design: For the selection of low voltage winding, either helical, cylindrical or cross over winding arrangements are preferred. Dimensions of the conductor of the low voltage winding is taken based on the area of the conductor.

5. High voltage winding design: Design of high voltage winding is similar to the low voltage winding design. Higher percentage of tapping increase the flexibility of transformer. Thus, helical or cross over winding arrangements are preferred in this case and dimensions of the conductor of the low voltage winding is taken based on the area of the conductor.

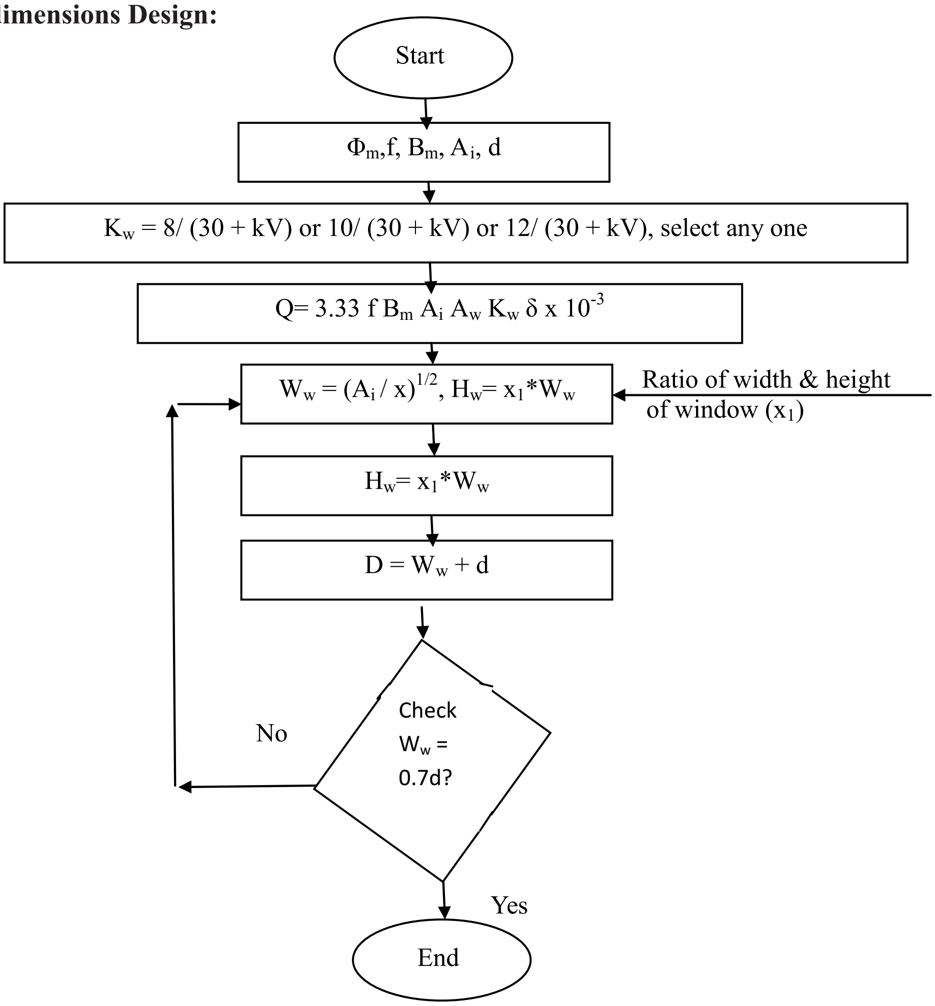
Flow charts for Transformer design:

Core design:

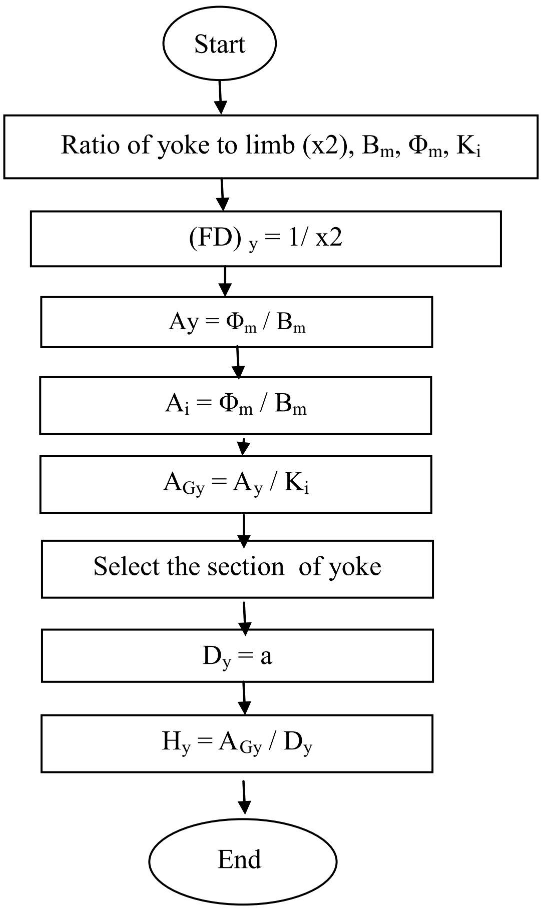


"x" indicates corresponding values of selected type of core.

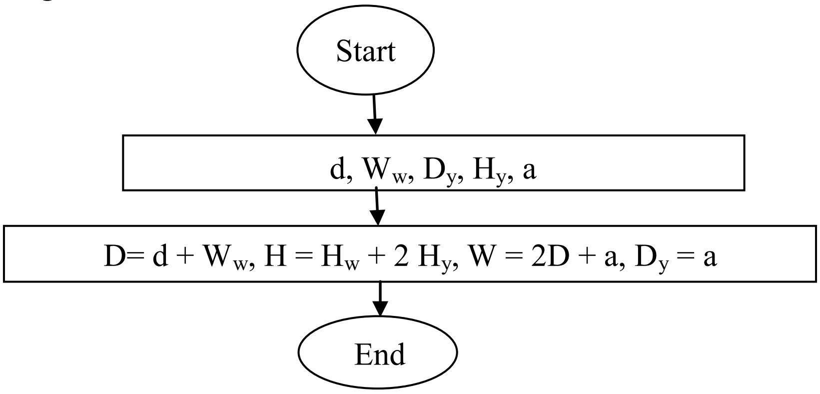
Start **Window dimensions Design:**



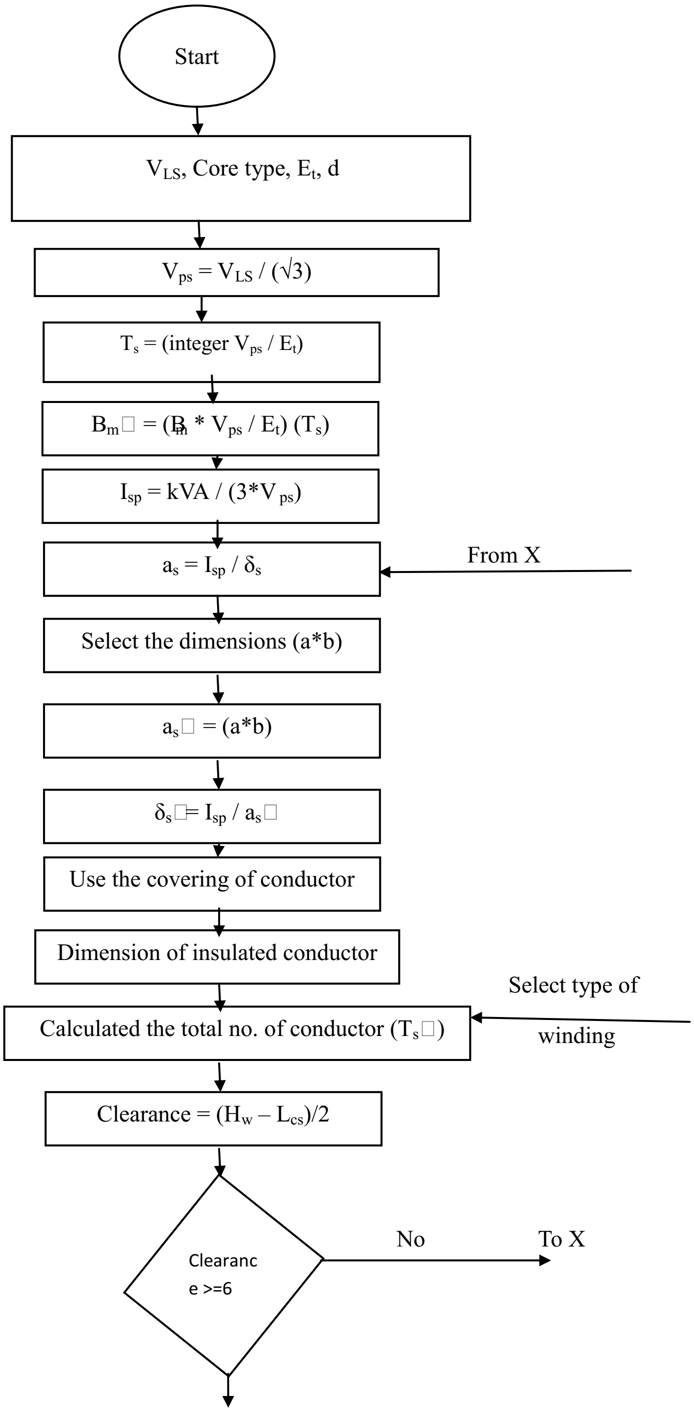
Yoke design:

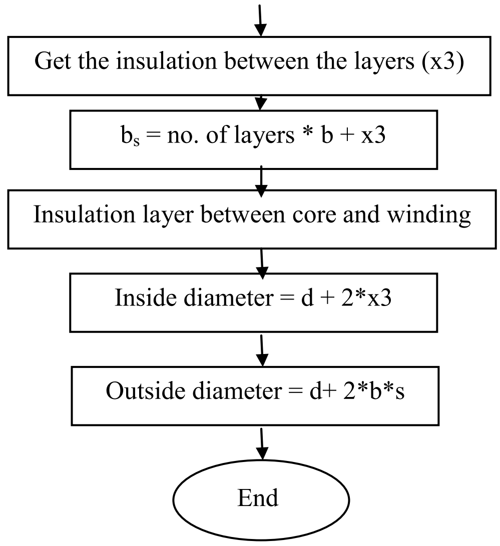


Overall dimensions design

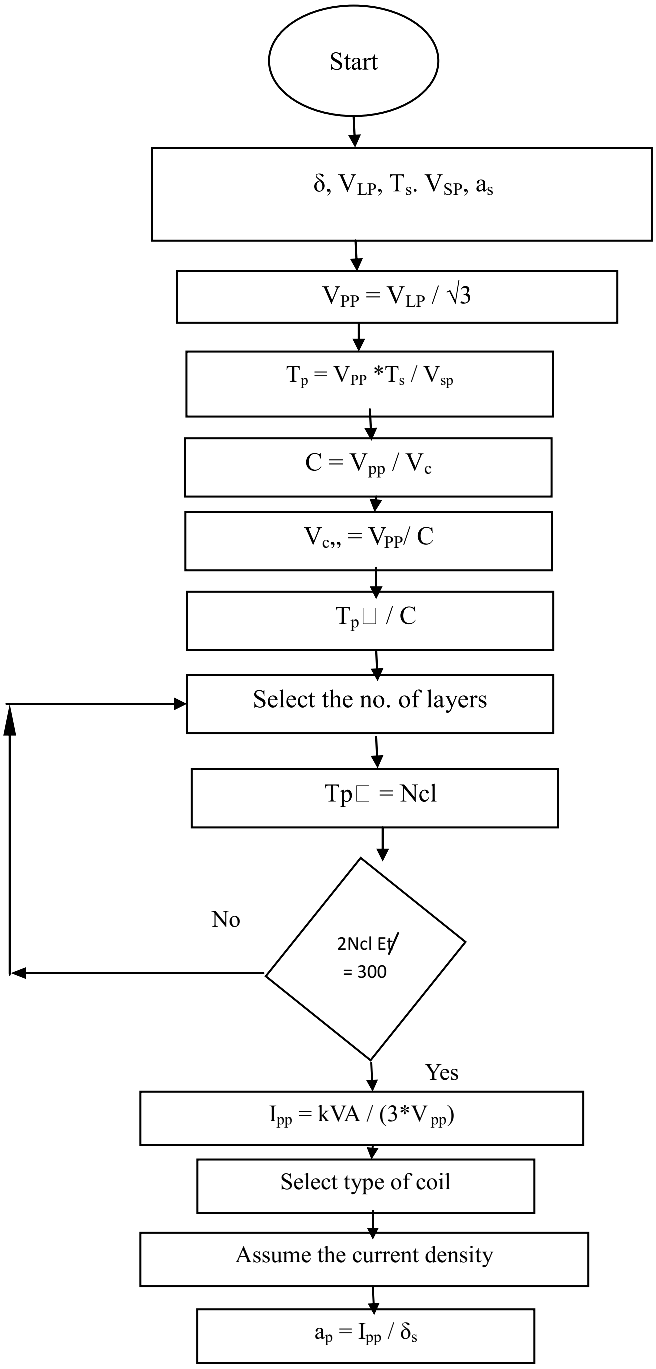


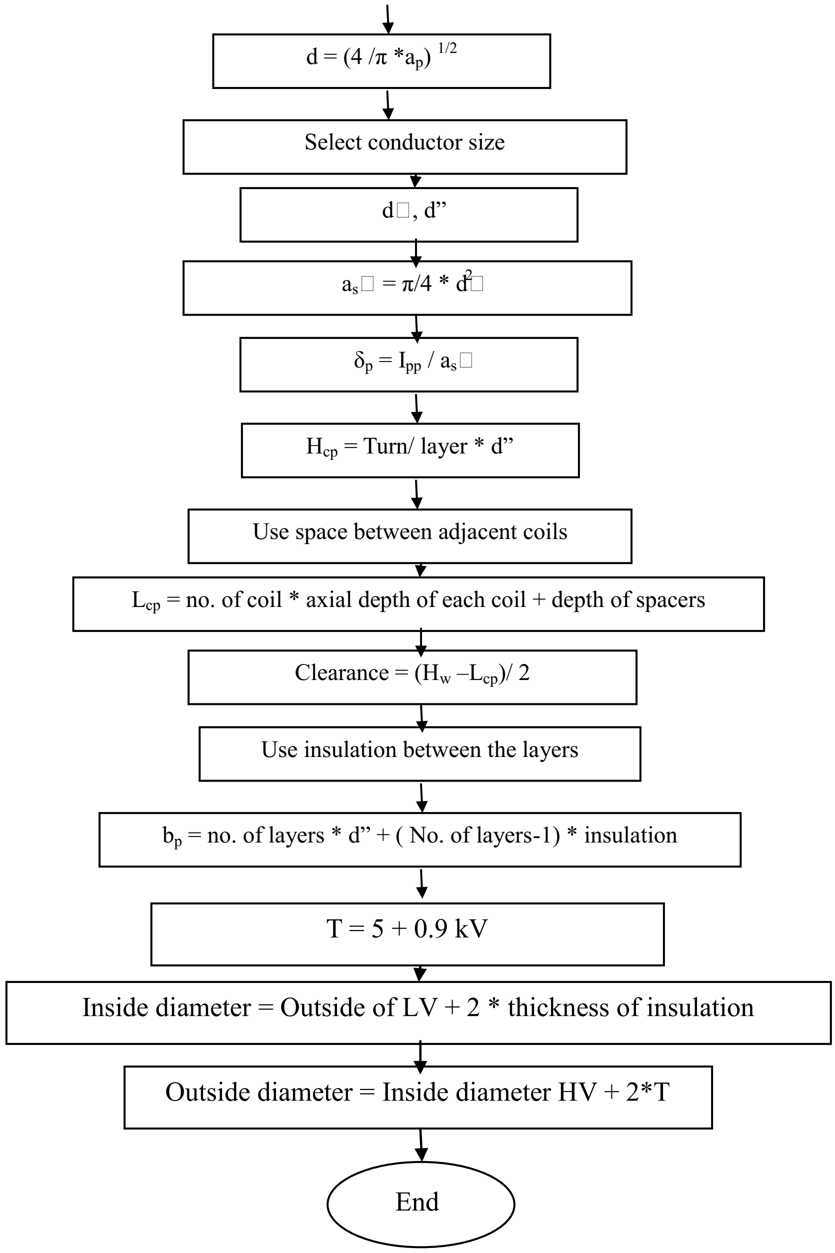
L.V. Winding design:



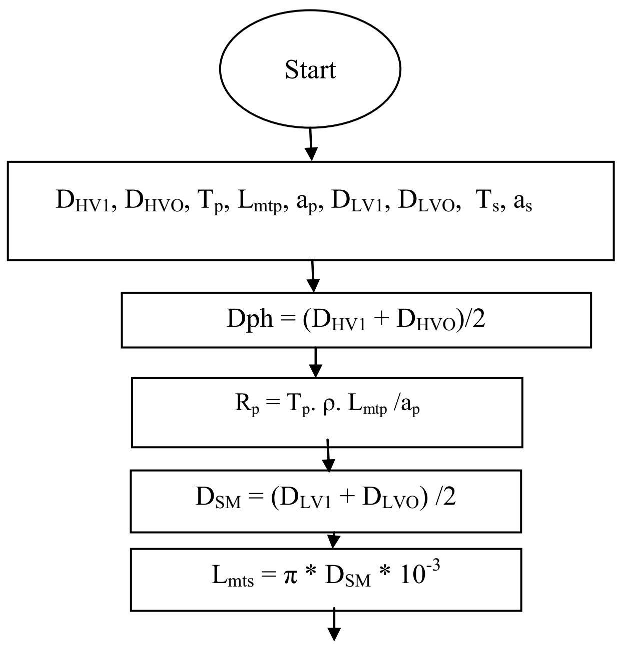


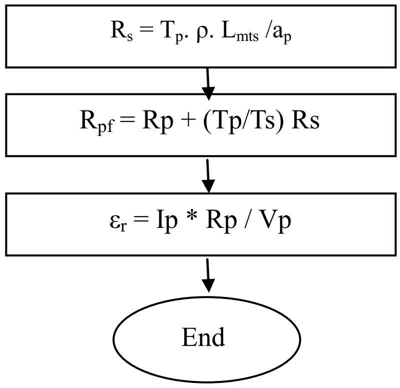
Winding design



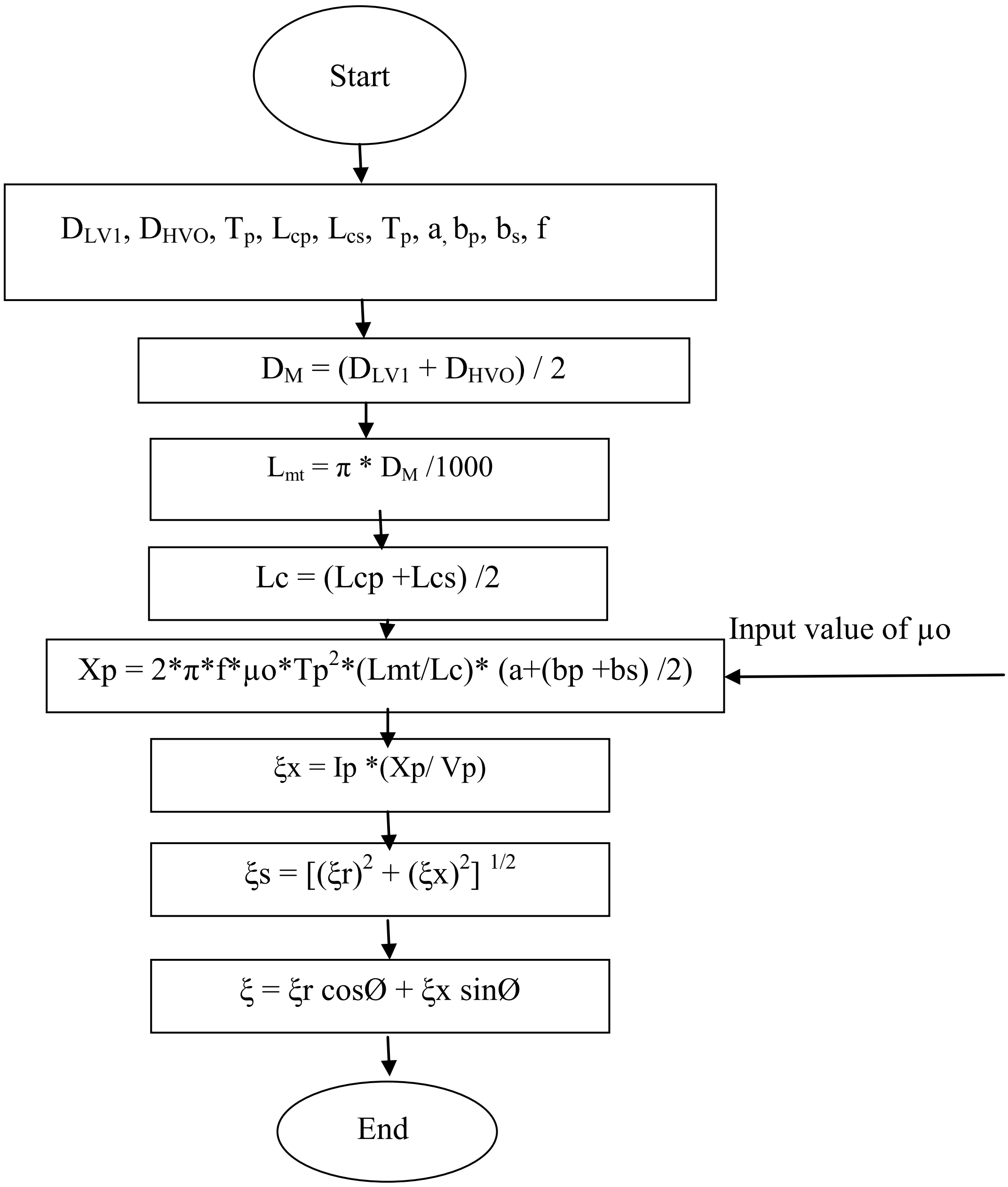


Resistance calculations

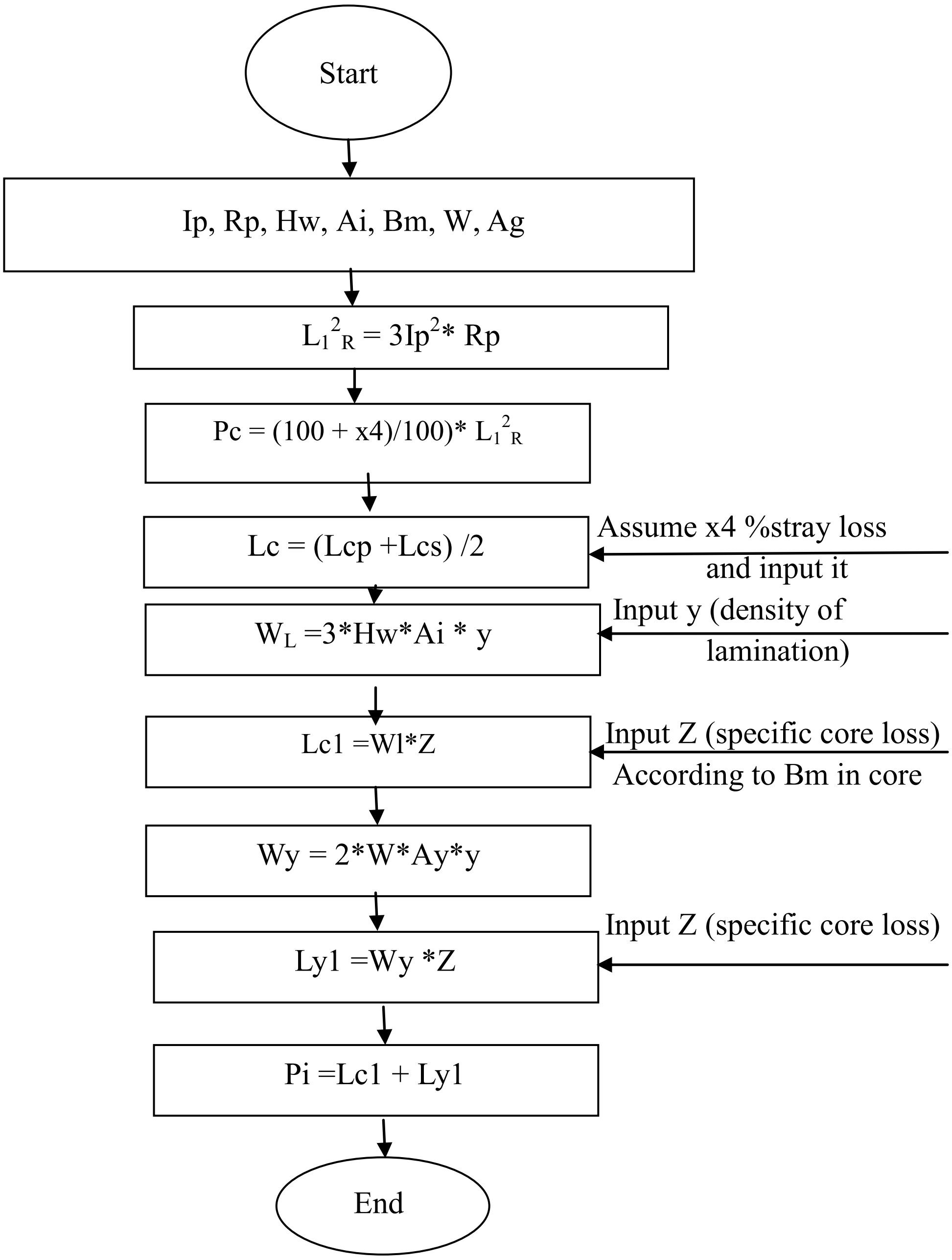




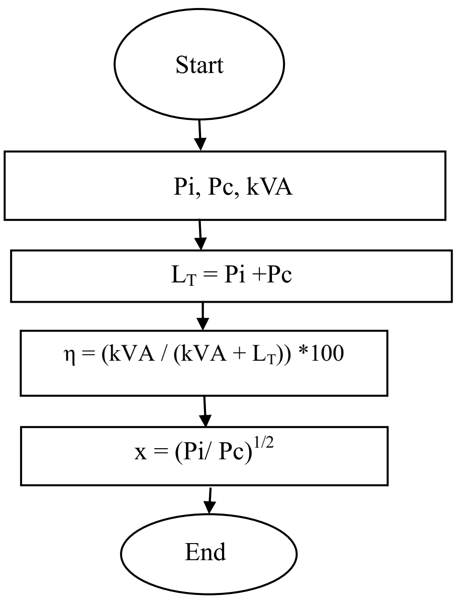
Leakage reactance calculations



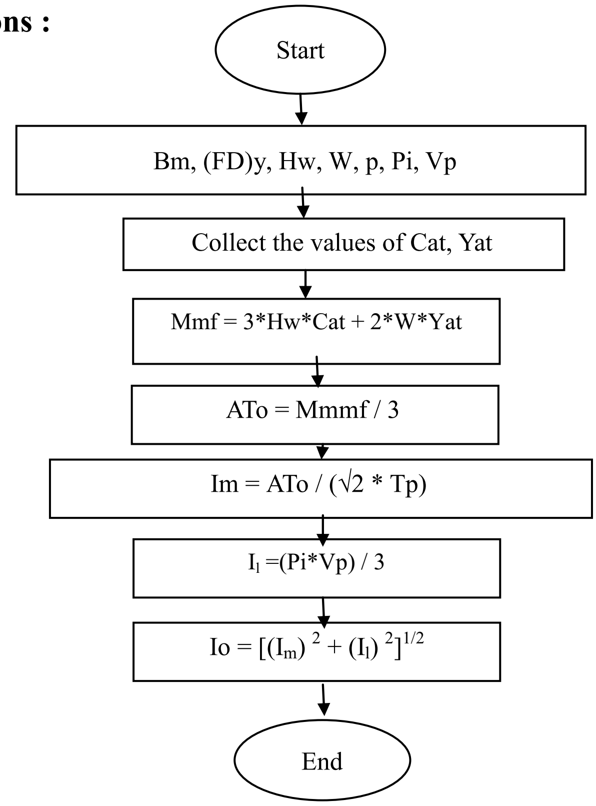
Loss calculations:



Efficiency calculations:



No load Current calculations :



Cat = value of ampere conductors per turn turns to the value of flux density in core

Yat = value of ampere conductors per turn turns to the value of flux density in yoke

Q. 8: Discuss the various optimization techniques. Apply any one technique for the design of synchronous machines

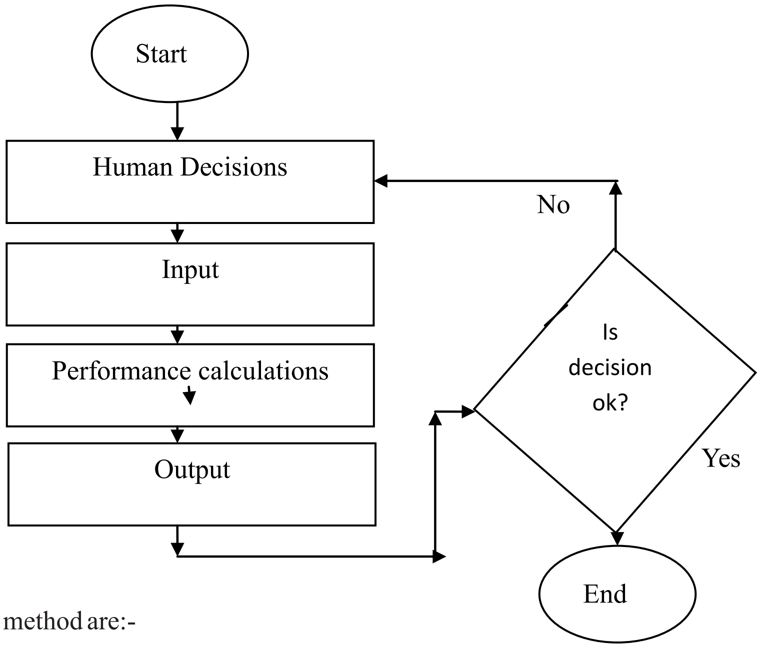
Sol: Computer Aided design-Different optimization approaches: The application of digital computers to the problem of electrical machine design was first introduced in 1950. In the early stage, this was limited to design of transformers. In the year 1956, the applications of digital computers are discussed to the design of transformers as well as rotating machines. In the same year, Veinatt published a research of application of digital computers for the design of induction motors. A flow chart was developed giving basic procedure for the design of polyphase induction motor. This paper in fact developed the analysis method for the design of polyphase induction motor.

The concept of optimization in electrical machine design was introduced by Godwin in 1959 and a program was developed for design of squirrel cage induction motors. In 1959, Heroz introduces the concept of two commonly acceptable approaches to machine design, namely:

I) Analysis method and ii) Synthesis method.

I) Analysis Method: The analysis method of design is depicted as in fig. In this method, the choice of dimensions, materials and type of construction are made by the designer and these are presented as input data to the computer. The performance was calculated by the computer and is returned to the designer for examination. The designer examines the performance and makes choice of input, if necessary and performance is recalculated. This procedure is repeated till the performance requirements are satisfied.

The use of term ”analysis method” means the use of computer for the purpose of analysis leaving all exercises of judgement to the designer.



The advantages of analysis method are:-

i) Easy to program, to use and to understand.

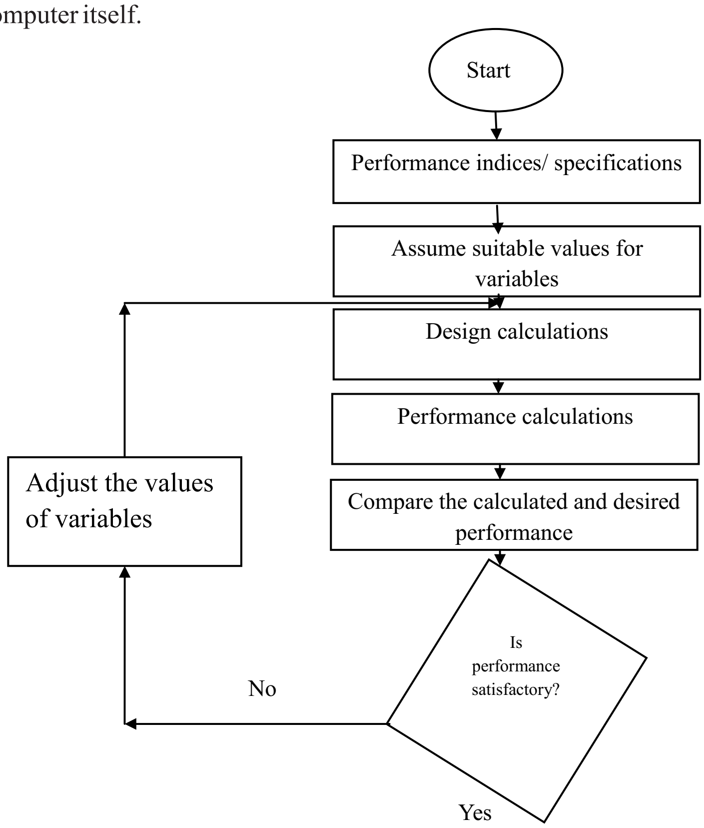
ii) It results in time saving thereby giving quick returns on investments.

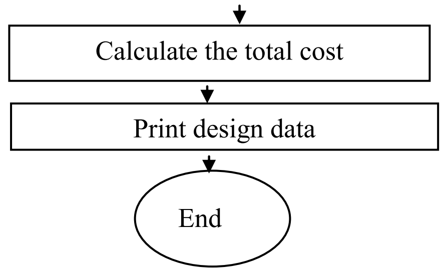
iii) Programs are simple.

iv) Highly acceptable results of analysis method by the designers.

i) Synthesis Method: The synthesis method is as depicted in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

The greatest advantage of synthesis method is as the saving in time in lapsed time and in engineering man hours on account of the decision left to the computer itself.





The synthesis method suffers with a number of serious disadvantages such as:-

1) This method involves too much logic since the logical decisions are left to the computer to take. Now, these logical decisions have to incorporated in the program and before, incorporation, the team of design engineers are to agree upon them.

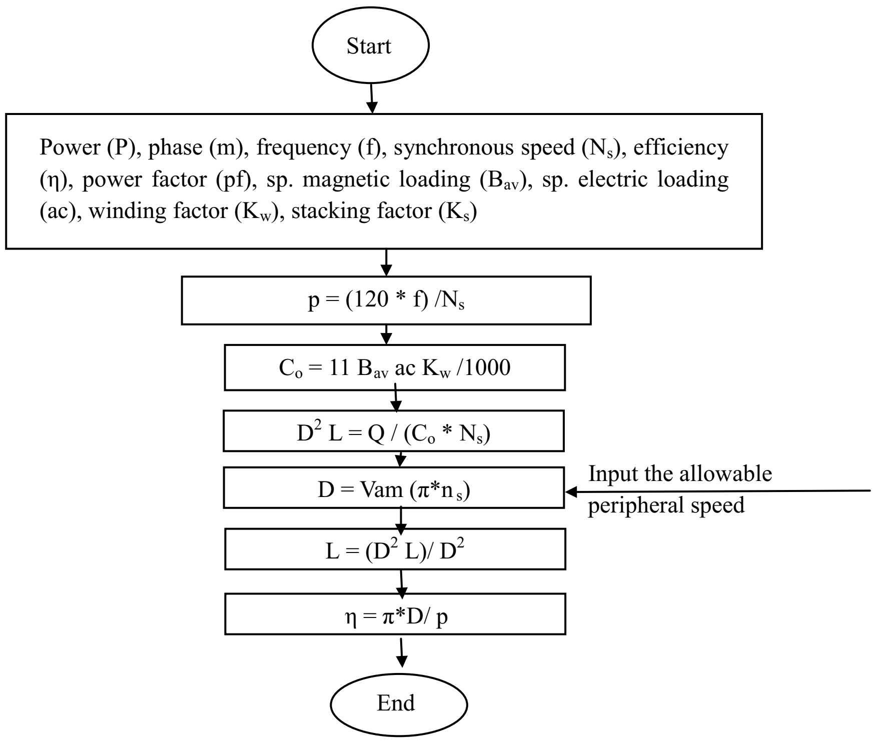
2) The logical decisions to arrive at a optimum design are too many and then, there are too many people with too many ways to suggest to produce the optimum design and thus, it becomes really hard to formulate a logic for obtaining an optimum design.

3) The formulation of a synthesis program taking into account of factors listed would make it too complex. So, cost of computer program becomes high and thus use of a large computer and also large running time involves huge expenditure.

4) The synthesis program formulated at a high cost cannot be used for ever, as due to changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions etc., the program has to be changed and up dated keeping. Thus synthesis method requires additional efforts and cost in order for the above.

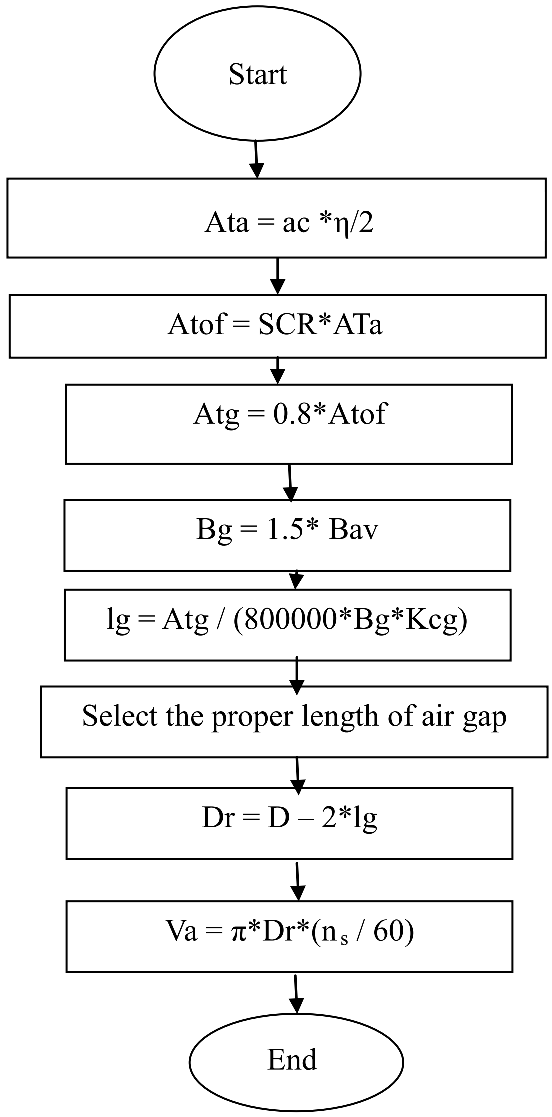
Design of synchronous machines using synthesis method: The flow chart for the design of synchronous machines is as follows for its complete design.

Main Dimensions:



Note: The value of maximum peripheral speed 175m/sec and its normal value is 130m/sec.

Length of air gap Design:

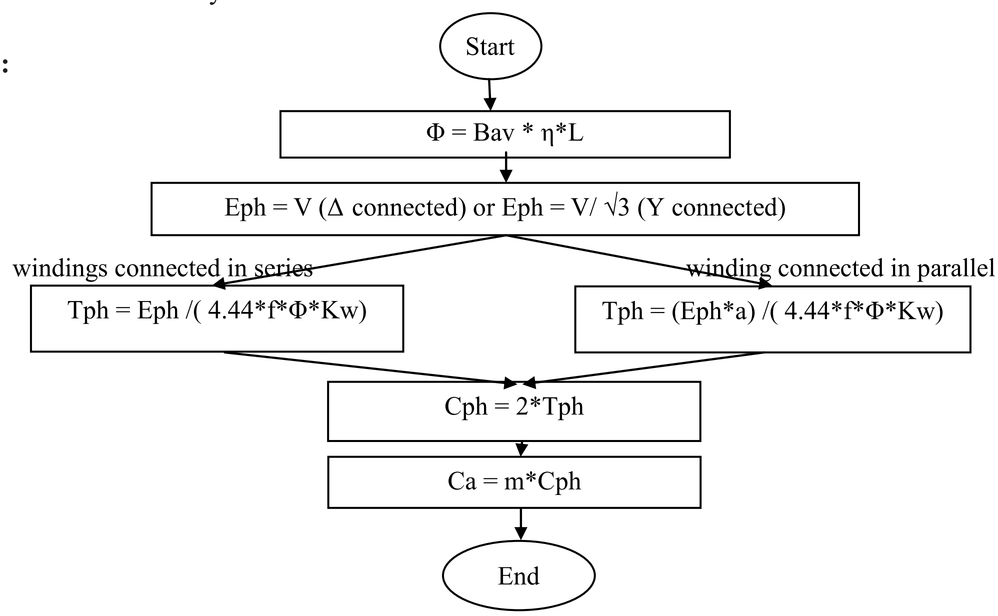


Note: The value of SCR (short-circuit ratio) of the machine is about 0.5 to 0.7

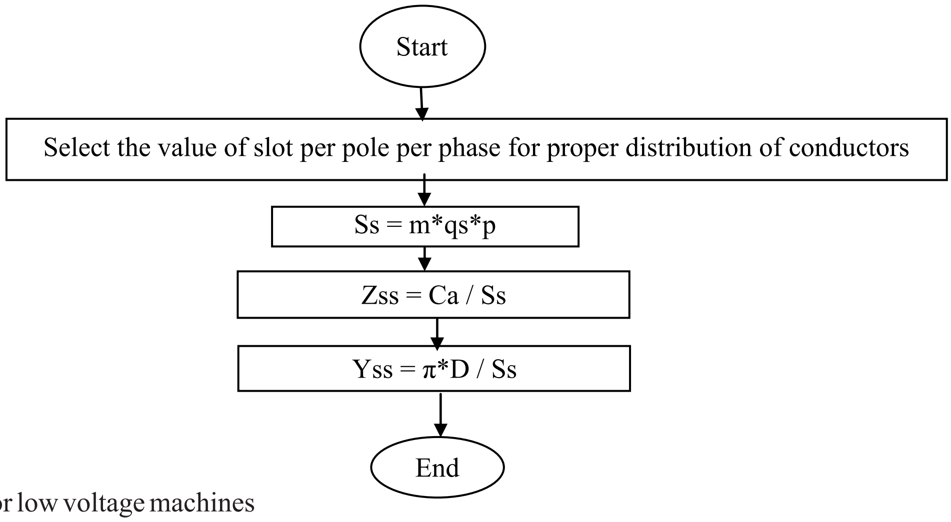
The ratio of air gap mmf to no load mmf is commonly constant value (80%)

The gap contraction factor is always 1.1.

Stator Design:



No. of slots:

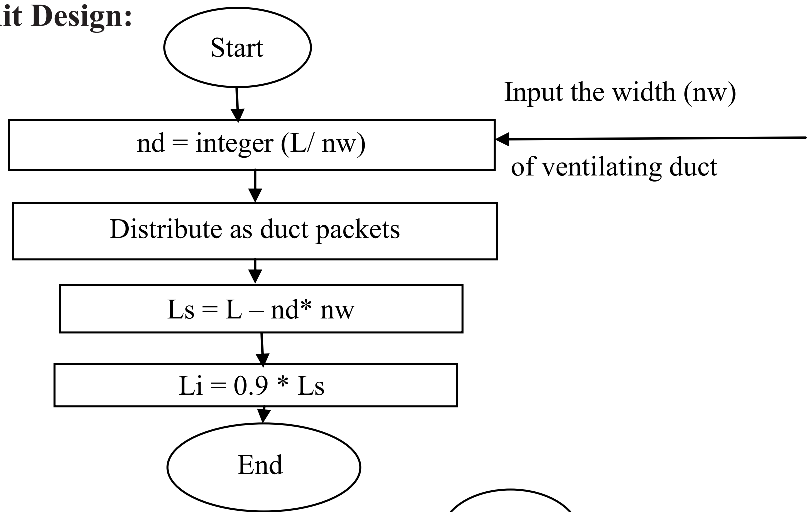


Note: Yss = 25 for low voltage machines

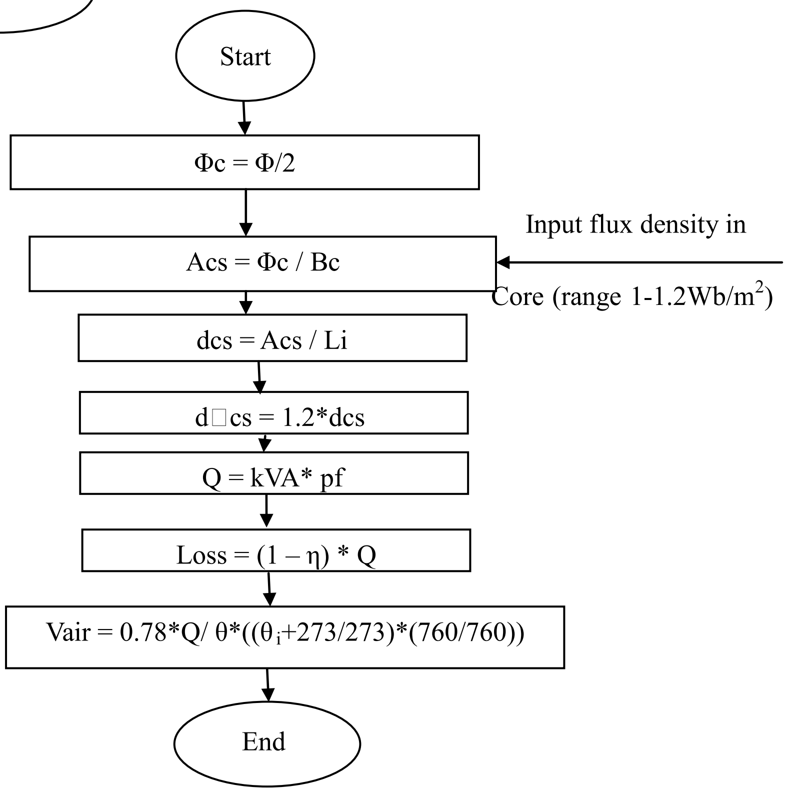
Yss= 10 for 6kV

Yss = 60 upto 15kV

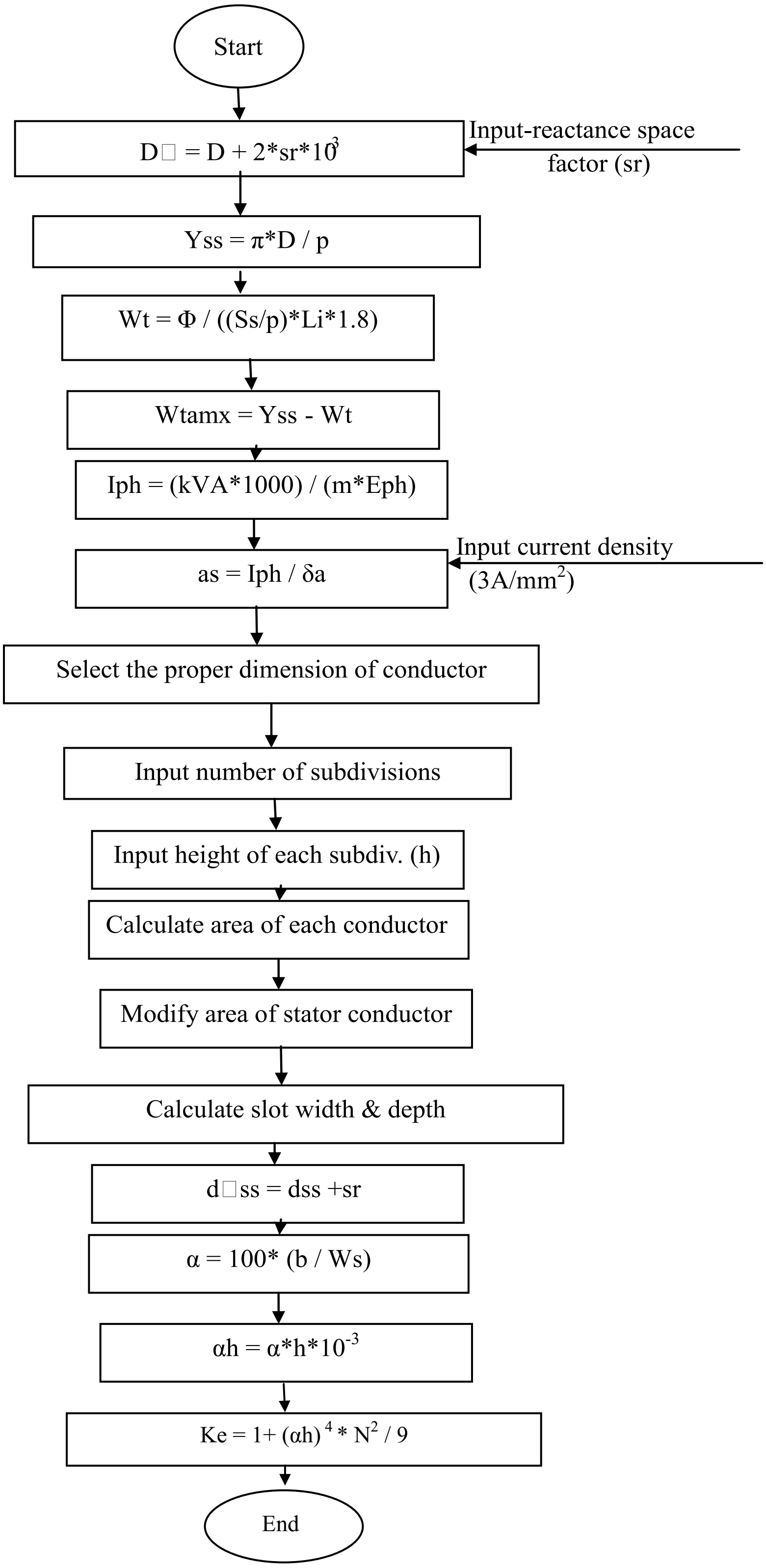
Magnetic circuit Design:



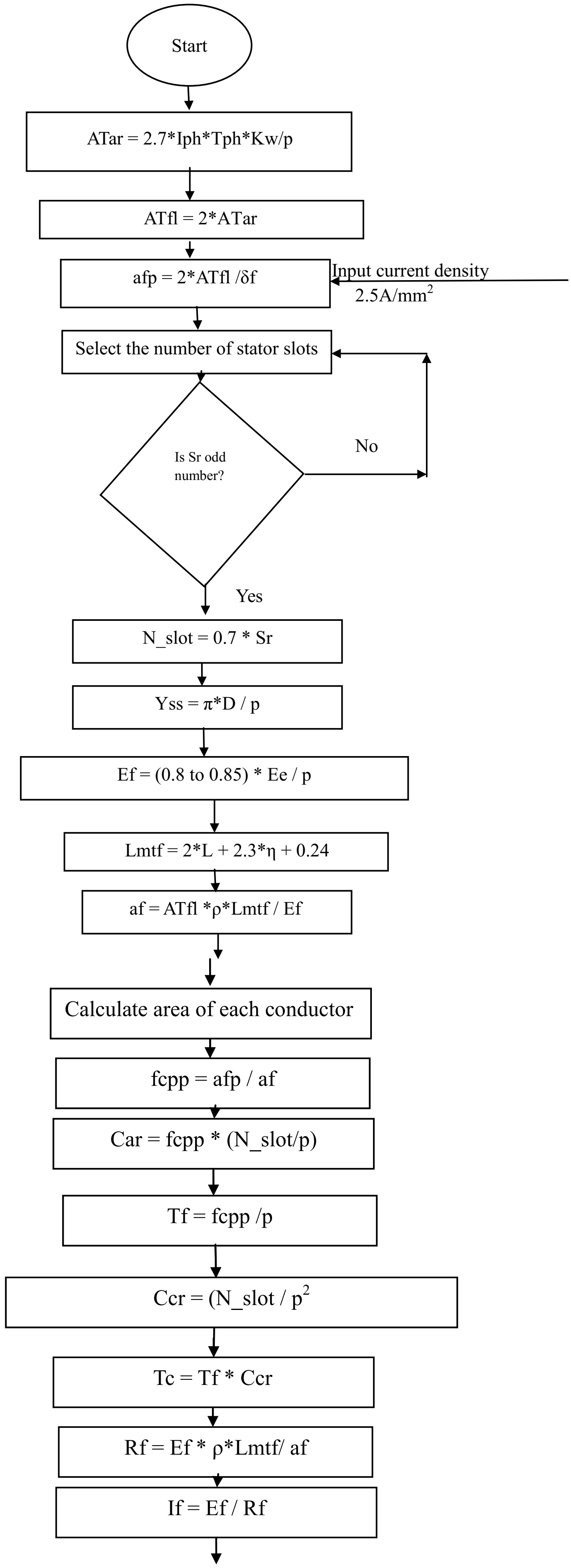
Stator Core Design:

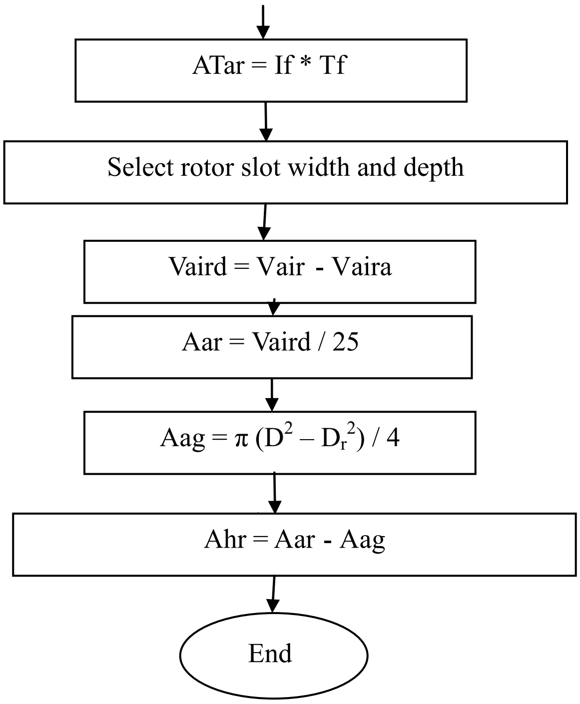


Slot Dimensions Design:



Rotor Design:





Electrical Machine Design

SOLVED QUESTION PAPER-6

Note: Attempt *Five* questions in all, selecting one question from each unit. All question carry equal marks.

Q. 1: a) Derive the output equation of a DC machine.

b) Describe the methods of measurement of temperature rise in various parts of an electrical machine.

Sol: a): Output equation of DC machines: The output equation of an electrical machine can be expressed in terms of its main dimensions, specific magnetic and electrical loadings and speed, the equation describing this relationship is as output equation.

<u>**DC Machine**</u>:

As power developed by armature in kW,

P_a = generated emf x armature current x 10^{-3}

But, $E = \Phi Z n p / a$

So, $P_a = \Phi Z n p / a \times I_a \times 10^{-3}$

$P_a = (p \Phi) [(I_a / a) \times Z] n \times 10^{-3}$

$P_a = (p \Phi) [I_z \times Z] n \times 10^{-3}$

P_a = (total magnetic loading) x (total electrical loading) x n x 10^{-3}

Here, specific magnetic loading, $B_{av} = (p \Phi) / (\pi D L)$ = (Total flux / area of each pole)

So, $\mathbf{p\,\Phi = B_{av} \times (\pi D L)}$

& specific electric loading, $ac = (I_z \times Z) / (\pi D)$

= total ampere conductor / perimetry of armature

So, $\mathbf{(Iz \times Z) = ac \times (\pi D)}$

Thus, power developed by the armature is, $\mathbf{P_a = C_o . D^2.L.n}$ $P_a = (1.11\pi^2 B_{av} \times ac \times 10^3) D^2 L n$

$$P_a = C_o . D^2.L.n$$

or, $$\text{output coefficient, } C_o = 1.11\pi^2 \times B_{av} \times ac \times 10^3$$

This is called as output equation of the dc machine.

b) Methods of measurement of temperature rise in electrical machines: The calculation of temperature rise of a machine is not simple due to complex heat flow through the materials having different conductivities and heat transfer coefficients. In order to ascertain whether sufficient provision has been made for cooling, heat runs are done during which the temperature rise are recorded against time. Thus, various methods of determining the temperature rise of windings and other parts are recognized:

a) Thermometer method

b) Resistance method

c) Embedded temperature detector method.

a) Thermometer method: In this method, the temperature is determined by thermometers applied to the accessible surface of the completed machine. Thermometer is usually applied to the surface of the machine part. So, it indicates the temperature of surface at one point only. The thermometer also includes non-embedded thermo-couples and resistance thermometers provided they are applied to the points accessible to the usual bulb thermometer. $R_2 / R_1 = (\theta_2 + 235) / (\theta_1 + 235)$

b) Resistance method: In this method, the temperature of winding is determined by increase in resistance of the winding. So, this method involves the measurement of the resistance, both cold and hot and estimating the average temperature rise by the use of resistance temperature coefficient. This method is used for winding only. The temperature rise, $\theta = \theta_2 - \theta_a$ may be obtained from the ratio of resistance by the formula:

$$R_2 / R_1 = (\theta_2 + 235) / (\theta_1 + 235)$$ (**Applicable for copper material only**)

where, R_2 = resistance of winding at the end of the test.

R_1 = initial resistance of winding

θ_2 = temperature (^{0}C) of winding at the end of test

θ_1 = temperature (^{0}C) of winding (cold) at the moment of initial resistance measurement

θ_a = temperature (^{0}C) of cooling medium at the end of test

So, temperature rise, $\theta = \theta_2 - \theta_a = [(R_2 - R_1) / R_1] \times (235 + \theta_1) + \theta_1 - \theta_a$

In the case of a.c. machines, resistance measurements may be made without interruption by **method of superposition**.

c) Embedded Temperature detectors (E.T.D.): Embedded temperature detectors are resistance thermometers or thermo-couples built into the machine during construction at points which are inaccessible when the machine is completed.

At least, six detectors are built into the machine, suitably distributed around the circumference and placed in positions along the length of the core at which highest temperature are likely to occur. The embedded detectors are provided with contact with cooling medium when the machine has two coil sides per slot, the detectors are located between the insulated coil-side within the slot. The embedded temperature detectors give the temperature of one **internal point**. In case, the embedded temperature detector can be placed, during the course of construction, at a point showing the highest temperature, gives the indication of **hot spot temperature**.

Q. 2: a) What are the major considerations in Electrical machine design?

b) Determine the apparent flux density in teeth of a DC machine if the real flux density in teeth is 2.15Wb/m^2, slot pitch is 28mm, slot width is 10mm, gross core length is 0.35m, no. of ventilating ducts is 4 each 10mm wide. Magnetizing force corresponding to flux density of 2.15 Wb/m^2 is 55000AT/m and iron stacking factor is 0.9

Sol: a): Major considerations in Electrical machine design: Design may be defined as a creative physical realization of theoretical concepts. Engineering design is application of science, technology and innovation to produce machines to perform specified tasks with optimum economy and efficiency.

The problem of design and manufacture is to build, as economically as possible, a machine which fulfils a certain set of specifications and guarantees. Thus, the major considerations to evolve a major design are:

1. Cost, 2. Durability, 3. Compliance with performance criteria as laid down in specifications.

A good design is one where is the machine has reasonable operating life and has a low initial cost. A design process is not merely engineering calculations bur involves careful consideration of the followings.

1. Design base: Matching the existing experience with Research and Development, bringing in the latest material technology, convenience in production line and transportation, working safely and reliability, maintenance and repair, environmental conditions, cost economy, optimization.

2. Specifications: Meeting with customer's requirements, guarantees, satisfy the national and international standards.

3. Design Transfer: Transfer of design to factory foremen, i.e. drawings, processes, instructions, job-flow, meeting with delivery schedule.

4. Information updating: Technical journals, R & D papers and reports, interaction in meetings and seminars.

Knowing the characteristics and specifications that a machine has to satisfy, the main areas of design are:-

a. The magnetic circuits: core, yoke and air gap.

b. The electric circuit- windings

c. The insulation.

d. Heating and cooling circuits.

e. The mechanical constructions.

Moreover economy in manufacturing costs, operating and running costs of the machine is also kept in view.

UNIT-II

Q. 3: a) Describe methods of cooling of transformer.

b) The ratio of flux to full load mmf in a 400kVA, 50 Hz single phase core type transformer is 2.4 x 10^{-6}. Calculate the net iron area and the window area of the transformer if the maximum flux density in the core is 1.3Wb/m^2, current density is 2.7A/mm^2 and window space factor is 0.26. Also calculate the full load mmf.

Sol: a): Methods of cooling of transformer: Various methods of cooling of the transformer are as under:

1. Air blast cooling.

2. Forced oil circulation.

Transformer oil as a cooling medium: It has been found that an average working temperature of the oil θ_0 = 50 to 60^{0}C and a viscosity corresponding to this temperature, the specific heat dissipation due to convection of oil is

$$\lambda_{conv.} = 40.3\ (\theta / H)^{1/4}\ W/m2\ \text{-}^0C$$

where, θ = temperature difference of the surface relative to oil, ^{0}C

H = height of dissipating surface, m

If assumed that, $\theta = 20^0C$ and H = 0.5 to 1m, then, $\lambda_{conv.}$ **= 80 to 100 W/m2 -^{0}C.**

The corresponding value for convection due to air is 8 W/m2 -^{0}C, but the convection of oil is 10 times better than that of air. Thus oil is better cooling agent in transformer.

1. Air blast cooling: At present time, radiators are forced cooled by small fans mounted on each radiator. Compared with natural cooling, air blast cooling of a tank mounted on each radiator. Compared with natural cooling, air blast cooling of a tank increases the heat dissipation by 50 to 60 percent or, heat dissipation now becomes,

$$\lambda = (1.5 \text{ to } 1.6) \times 12.5 \text{ W/m2 -}^0C$$

2. Forced oil Circulation: The velocity with which the natural oil circulation takes place is very low, of the order of a few mm/sec. Further, if the velocity of the circulation of oil is increased by m times, the output of the transformer is increased by $(m)^{1/4}$ times. Further, an excessive increase in oil circulation rate, the large energy losses in the pumping unit takes place and thus oil is to be cooled by separate oil cooler.

In an air cooler with natural air cooling, the flow rate of the circulating oil is of the order of 12 litres per minute per kW of losses, whereas, in air blast cooler, the transformer output increases roughly to the same extent as when the tank is air blast cooled.

b): Given that, for a single phase core type transformer,

$$(\text{flux } \Phi_m / \text{full load mmf, AT}) = 2.4 \times 10^{-6}$$

or, $$\Phi_m / (I \times T) = 2.4 \times 10^{-6}$$

As per transformer output equation, we get

$$\mathbf{K = \sqrt{(4.44 \times f \times (\Phi_m / (I \times T) \times 10^3)} = 0.732}$$

and voltage per turn, $E_t = K \times \sqrt{(Q)}$

where, Q – kVA rating of transformer = 400kVA

So, $$E_t = 0.732 \times \sqrt{(400)} = 14.64V$$

& flux in transformer, $\Phi_m = E_t / (4.44 \times f) = 14.64 / (4.44 \times 50) = 0.066Wb$

So, **Net iron area,** $\mathbf{A_i = \Phi_m / B_m = 0.066 / 1.3 = 0.0507m^2}$

Thus, window area of the transformer, A_w from output equation, is

$$Q = 2.22 \times f \times B_m \times A_w \times A_i \times \delta \times K_w \times 10^{-3}$$

where, δ = current density = 2.7 A/mm^2 = 2.7×10^6 A/m^2

Thus, $$\mathbf{A_w = Q / (2.22 \times f \times B_m \times A_i \times \delta \times K_w \times 10^{-3}) = 0.0777m^2}$$

AT = 27500A Full load mmf, **AT = Φm / (2.7 x 10^{-6}) = 27500A**

AT = 27500A

Q. 4: a) Derive the output equation of a single phase transformer in terms of core and window area.

b) Derive the expression for length of air gap of a synchronous machine.

Sol: a): Output equation of a single phase transformer:

Let, Φ_m = main flux, Wb,

B_m = maximum flux density, Wb/m^2,

δ = current density, A/mm^2,

A_{gi} = gross core area, m^2

A_i = net iron area, m^2 = stacking factor x gross core area

A_c = area of copper in the window, m^2

A_w = area of the window, m^2

D = distance between core centres, m

d = diameter of circumscribing circle, m

K_w = window space factor

f = frequency, Hz

E_t = emf per turn, V

T_p, T_s = no. of turns of primary and secondary windings

I_p, I_s = current in primary and secondary windings, A

V_p, V_s = terminal voltage in primary and secondary windings, V

a_p, a_s = area of conductors of primary and secondary windings, m^2

l_i = mean length of flux path in the iron, m

L_{mt} = length of mean turn of winding, m

G_i = weight of active iron, Kg

G_c = weight of copper, Kg

g_i = weight of iron per m^3

g_c = weight per m^3 of copper

p_i = losses in iron per kg, W

p_c = losses in copper per kg, W

For a single phase core type transformer: The voltage induced in a transformer winding with T turns and excited by a source having a frequency f Hz is given by

Voltage per turn, $E_t = E / T = 4.44 \times f \times \Phi_m$

The window of transformer contains one primary and one secondary winding.

Thus,

Total copper area in window, A_c = copper area 1^0 wdg. + Copper area in 2^0 wdg.

or, $A_c = 1^0$ turns x area of 1^0 conductor + 2^0 turns x area of 2^0 conductor

or, $\mathbf{A_c = T_p \times a_p + T_s \times a_s}$

Taking the current density is same in both the 1^0 and 2^0 windings, thus,

$a_p = I_p / \delta$ & as = I_s / δ

So, $\mathbf{A_c = Tp \times Ip / \delta + Ts \times Is / \delta = 2\,AT / \delta}$

(as, $T_p I_p = T_s I_s = AT$)

The window space factor Kw, is defined as ratio of copper area in window to total window area.

Thus, Kw = conductor area in window / total area of window = A_c / A_w

So, **conductor area in window $\mathbf{A_c = K_w \times A_w}$**

or, $2\,AT / \delta = K_w \times A_w$

or, $\mathbf{AT = K_w \times A_w \times \delta / 2}$

As rating of single phase transformer is,

$$Q = V_p . I_p . 10^{-3} = E_p . I_p . 10^{-3} = Et . T_p . I_p . 10^{-3} = E_t \times (AT) \times 10^{-3}$$

or, $Q = E_t \times (K_w \times A_w \times \delta / 2) \times 10^{-3} = 4.44 \times f \times \Phi_m \times (K_w \times A_w \times \delta / 2) \times 10^{-3}$

or, $\mathbf{Q = 2.22 \times f \times \Phi_m \times K_w \times A_w \times \delta \times 10^{-3}}$ **kVA**

But, $\Phi_m = B_m \times A_i$

Thus, output equation of 1-phase transformer is,

$$\mathbf{Q = 2.22 \times f \times B_m \times A_i \times K_w \times A_w \times \delta \times 10^{-3}} \text{ kVA}$$

b): Length of air gap: The length of air gap influences the performance of a synchronous machine. A large air gap offers a large reluctance to the path of flux produced by the armature mmf and thus reduces the effect of armature reaction. This results in a small value of synchronous reactance and a high value of SCR. Thus a machine with a large air gap (with a small X_d and high SCR) has

i) a small value of inherent regulation.

ii) a higher value of stability limit

iii) a higher synchronizing power which makes the machine less sensitive to load variations.

In addition, a machine designed with a large air gap has better cooling at a gap surface, lower tooth pulsation loss, lower noise level and a smaller unbalanced magnetic pull. But with the large value length of the air gap, a larger value of field mmf is required resulting in increase of cost of the machine.

For salient pole machine of normal construction and having open type slots,

Length of air gap / pole pitch = lg / τ = 0.01 to 0.015

For turbo-alternators with massive rotors,

Length of air gap / pole pitch = lg / τ = 0.02 to 0.025

For synchronous motors designed with maximum output 1.5 times rated output,

Length of air gap / pole pitch = lg / τ = 0.02

UNIT-III

Q. 5: A 15kW, 400V, 3-phase, 50Hz, 6-pole, induction motor has a diameter of 0.3m and the core length of 0.12m. The number of stator slots is 72 with 20 conductors per slot. The stator is delta connected. Calculate the value of magnetizing current per phase if the length of air gap is 0.55m. The gap contraction factor is 1.2. Assume the mmf required for iron parts to be 35% of the air gap mmf. Coil span = 11 slots.

Sol: Given that, power output = 15kW

Input voltage, V= 400V

f = 50Hz

no. of poles, P =6

armature diameter, D = 0.3m

core length, L =0.12m

No. of stator slots = 72

So, **no. of slots per pole per phase, q = 72 / (3 x 6) = 4**

No. of slots per pole = 72 / 6 = 12

Given, coil span = 11 slots

This is a chording or short pitch winding with short-pitch angle, ε is.

ε = (no. of short pitching slots / slot pitch) x 180^0 = 1/12 x 180 = 15^0

Thus, distribution factor, K_d = sin (q σ / 2) / [q sin (σ / 2)]

K_d = sin (4 x 15/2) / [4 sin (15/2)] = 0.958

& **coil pitch factor, K_p = Cos (ε/2) = Cos (15/2) = 0.9914**

So. **Stator winding factor, K_{ws} = K_d x K_p = 0.958 x 0.9914 = 0.95**

Now, total stator conductors, Z_s = no. of conductors per slot x total no. of slots

or, Z_s = 72 x 20 = 1440

Stator turns per phase, T_s = Z_s / 6 = 1440 /6 = 240

As the induction motor is delta connected. Thus, per phase stator voltage is,

E_{ph} = E_L = 400V

So, flux per pole, $\Phi_m = E_{ph} / (4.44 \text{ x } f \text{ x } K_{ws} \text{ x } T_s) = 7.9 \text{ x } 10^{-3}$ Wb

Area per pole = π D L / P = (π x 0.3 x 0.12) / 6 =18.85 x 10^{-3} m^2

So, **average flux density, B_{av} = Φ_m /Area per pole = 0.418 Wb/m^2 B_{g60} = 1.36 B_{av} = 1.36 x 0.418 = 0.57 Wb/m^2**

For the mmf for air gap, the gap flux density at air gap at 60^0 is,

B_{g60} = 1.36 B_{av} = 1.36 x 0.418 = 0.57 Wb/m^2

So, mmf for air gap, AT_g = 800,000 x B_{g60} x K_g x l_g

Where, l_g = length of air gap = 0.55m, K_g = gap contraction factor = 1.2

AT_g == 800,000 x 0.57 x 1.2 x 0.55 x 10^{-3} = 301A

As given, mmf for iron path = 35 % of air gap mmf = 0.35 x 301 = 105.35A

Total mmf AT_{60} = AT_g + AT_i = 406.35A

Thus, the magnetizing current per phase,

I_m = 0.427 p AT_{60} / (K_{ws} T_s) = 4.56A

Q. 6: a) Discuss the factors to be considered in estimating the length of air gap of a induction motor.

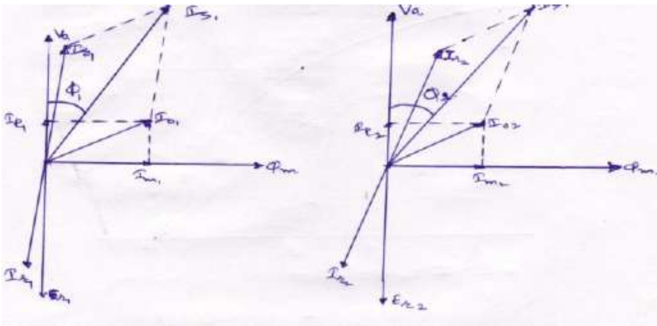
b) Find the main dimensions of a 15kW, 3-phase, 400V, 50Hz, 2810rpm squirrel cage induction motor having an efficiency of 0.88 and a full load power factor of 0.9. Assume specific magnetic loading = 0.5Wb/m^2, specific electric loading = 25000AT/m. Take the rotor peripheral speed as approximate 20m/sec at synchronous speed.

Sol: a): Length of air gap in 3-phase induction motor: The following factors should be considered while estimating the length of air gap:-

1. **Power Factor**: The mmf required to send the flux through the air gap is proportional to the product of flux density and

length of air gap. So, it is length of air gap that primarily determined the magnetizing current drawn by the machine, as if the flux densities are low, the mmf required for the air gap is much more than the rest of the magnetic circuit.

Fig. shows the phasor diagrams of an induction motor with two different gap lengths where, V_s = stator applied voltage, Φ_m = air gap flux, E_r = rotor induced emf, I_r = rotor current, I_r' = rotor current referred to the stator side, I_m = magnetizing current, I_L = Loss component of no-load current, I_0 = no-load current, I_s = stator current and Ø = phase angle between stator voltage and stator current.



From the above phasor diagrams, the magnetizing current in case 2 is greater than that of case 1 and thus, the phase angle between the stator voltage and stator current is greater in case 2 i.e. $Ø_2$ is greater than $Ø_1$, or Cos $Ø_2$ is smaller than Cos $Ø_1$. Hence, the power factor of machine with a greater air gap length is smaller.

2. Overload capacity: The over-load capacity of the induction motor is defined as ratio of maximum output to the rated output.

The length of air gap affects the value of total leakage reactance in the case of induction motor. If the length of air gap increases, the total leakage reactance reduces and thus overload capacity increases. So, greater is the length of air gap, greater is the overload capacity.

1. Pulsation Loss: With larger length of air gap, variation of reluctance due to slotting is small and the tooth pulsation losses, due to variation in the reluctance of air gap, is reduced. Hence, the pulsation loss is less with large air gap.

4. Cooling: If length of air gap is large, surface of rotor and stator are separated by a large distance. This would afford better cooling at the gap surfaces.

1. Noise: the principle cause of noise in the induction motor is the variation of reluctance of path of leakage flux. To ensure to reduce the noise, it is necessary to reduce the leakage flux as small as possible. This can be done by increasing the air gap length.

So, it is concluded that the length of air gap in a induction motor should be as small as possible in order to keep magnetizing current small and to improve the power factor.

Calculation of air gap length:

i) For small induction motors, the length of air gap is estimated as,

$$l_g = 0.2 + 2\sqrt{(DL)}, \text{ mm.}$$

ii) Another expression, which can be used for small machines, is

$$l_g = 0.125 + 0.35\,D + L + 0.015\,V_a, \text{ mm}$$

iii) Another formula is,

$$l_g = 0.2 + D, \text{ mm}$$

b): Given, kVA, Q = kW/ (CosØ x η) = 18.94kVA

Output coefficient, $C_o = 11\,K_w\,B_{av}\,ac \times 10^{-3}$

Given, B_{av} = sp. magnetic loading = 0.5Wb/m^2

ac = sp. electric loading = 25000A/m

Take, K_w = winding factor = 0.955

Thus, C_o = 131.3

The speed of rotor at full load is 2810rpm and the nearest synchronous speed (N_s) corresponding to 50Hz is 3000rpm.

Thus, synchronous speed, $n_s = 3000 / 60 = 50$ r.p.sec.

So, **product (volume), $D^2 L = Q / (C_o n_s) = 2.88 \times 10^{-3}\ m^3$**

As the rotor peripheral speed = 20 m/sec

or $\pi D n_s = 20$

So, **D = 0.1275 m.** and **L = 0.177m**

UNIT-IV

Q. 7: a) Discuss the merits of using digital computers in designing the electrical machines.

b) Explain in brief various optimization techniques.

Sol: a): Merits of Computer Aided Machine design: The digital computer has completely revolutionized the field of design of electrical machines. The computer aided design eliminates the tedious and time consuming hand calculations. The use of computer makes possible more trial designs. Thus, the advantages of use of a digital computer for the design of electrical machines may be as under:-

1. It has capabilities to store amount of data, count integers, round off results down to integers and refer to tables, graphs and other data in advance.

2. It makes it possible to select an optimized design with a reduction in cost and improvement in performance.

3. A large number of loops can be incorporated in the design programme and thus, makes it easier to compare different designs and best one can be selected.

4. It performs all simple arithmetic operations at a high speed and makes it possible to produce a design at a shorter time.

5. It is capable of automatic operation f design programme.

6. It reduces the probability of errors with highly accurate and reliable results.

7. Larger manufacturing savings can be obtained by optimization of design by use of computers.

8. It is capable of taking logical decisions by itself.

The high rate of performing calculations at reasonable cost and the ability to carry out logical decisions are the most important qualities of the present digital computers. Thus, the digital computers have been responsible for "complete revolution" in the field of electrical machine design.

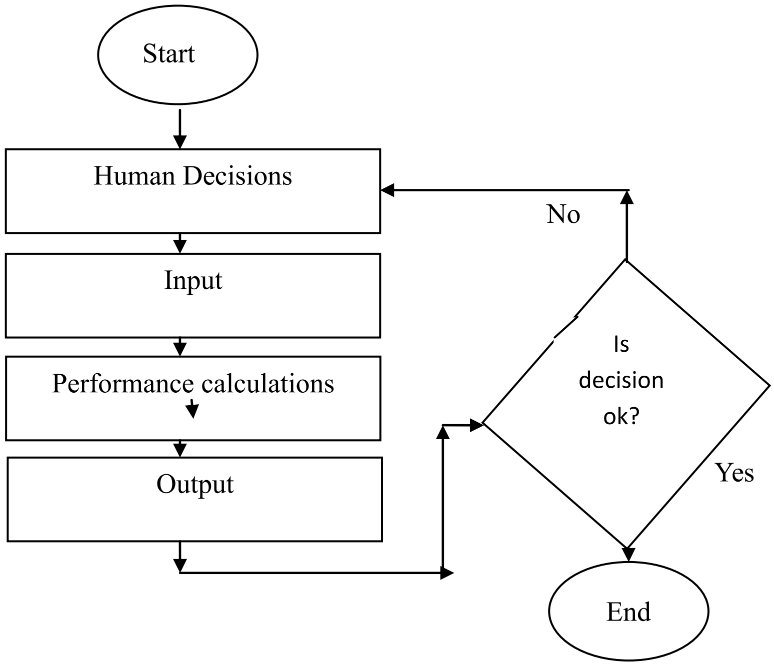
b): Different optimization approaches: The application of digital computers to the problem of electrical machine design was first introduced in 1950. In the early stage, this was limited to design of transformers. In the year 1956, the applications of digital computers are discussed to the design of transformers as well as rotating machines. In the same year, Veinatt published a research of application of digital computers for the design of induction motors. A flow chart was developed giving basic procedure for the design of polyphase induction motor. This paper in fact developed the analysis method for the design of polyphase induction motor.

The concept of optimization in electrical machine design was introduced by Godwin in 1959 and a program was developed for design of squirrel cage induction motors. In 1959, Heroz introduces the concept of two commonly acceptable approaches to machine design, namely:

i) Analysis method and ii) Synthesis method.

I) Analysis Method: The analysis method of design is depicted as in fig. In this method, the choice of dimensions, materials and type of construction are made by the designer and these are presented as input data to the computer. The performance was calculated by the computer and is returned to the designer for examination. The designer examines the performance and makes choice of input, if necessary and performance is recalculated. This procedure is repeated till the performance requirements are satisfied.

The use of term "analysis method" means the use of computer for the purpose of analysis leaving all exercises of judgement to the designer.



The advantages of analysis method are:-

i) Easy to program, to use and to understand.

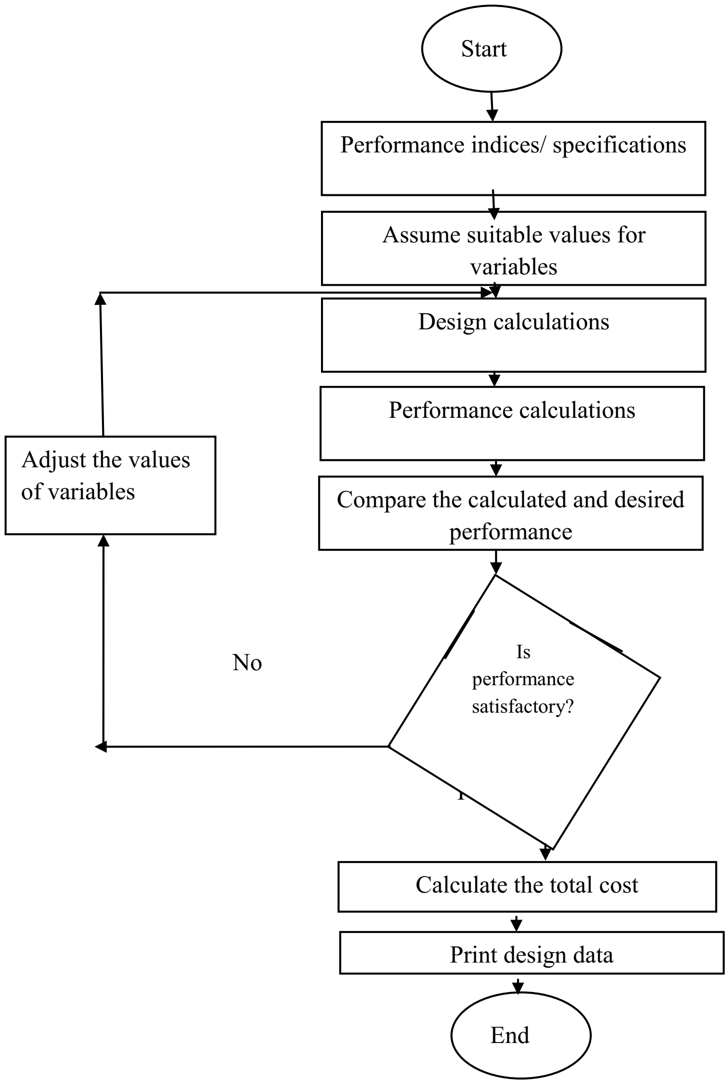
ii) It results in time saving thereby giving quick returns on investments.

iii) Programs are simple.

iv) Highly acceptable results of analysis method by the designers.

I) Synthesis Method: The synthesis method is as depicted in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

The greatest advantage of synthesis method is as the saving in time in lapsed time and in engineering man hours on account of the decision left to the computer itself.



The synthesis method suffers with a number of serious disadvantages such as:-

1) This method involves too much logic since the logical decisions are left to the computer to take. Now, these logical decisions have to incorporated in the program and before, incorporation, the team of design engineers are to agree upon them.

2) The logical decisions to arrive at a optimum design are too many and then, there are too many people with too many ways to suggest to produce the optimum design and thus, it becomes really hard to formulate a logic for obtaining an optimum design.

3) The formulation of a synthesis program taking into account of factors listed would make it too complex. So, cost of computer program becomes high and thus use of a large computer and also large running time involves huge expenditure.

4) The synthesis program formulated at a high cost cannot be used for ever, as due to changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions etc., the program has to be changed and up dated keeping. Thus synthesis method requires additional efforts and cost in order for the above.

i) Hybrid Method: This method incorporates both the analysis as well as synthesis methods in the program. Since the synthesis methods involve greater cost, the major part of the program is based upon the analysis with a limited portion of the program being based upon synthesis.

Q. 8: a) Explain design procedure can be computerized. Explain with the help of block diagram.

b) How problem is designed using optimization techniques.

Sol: a): Design procedure using computer (Synthesis Method): The computerised method of design is as depicted as the synthesis method as in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

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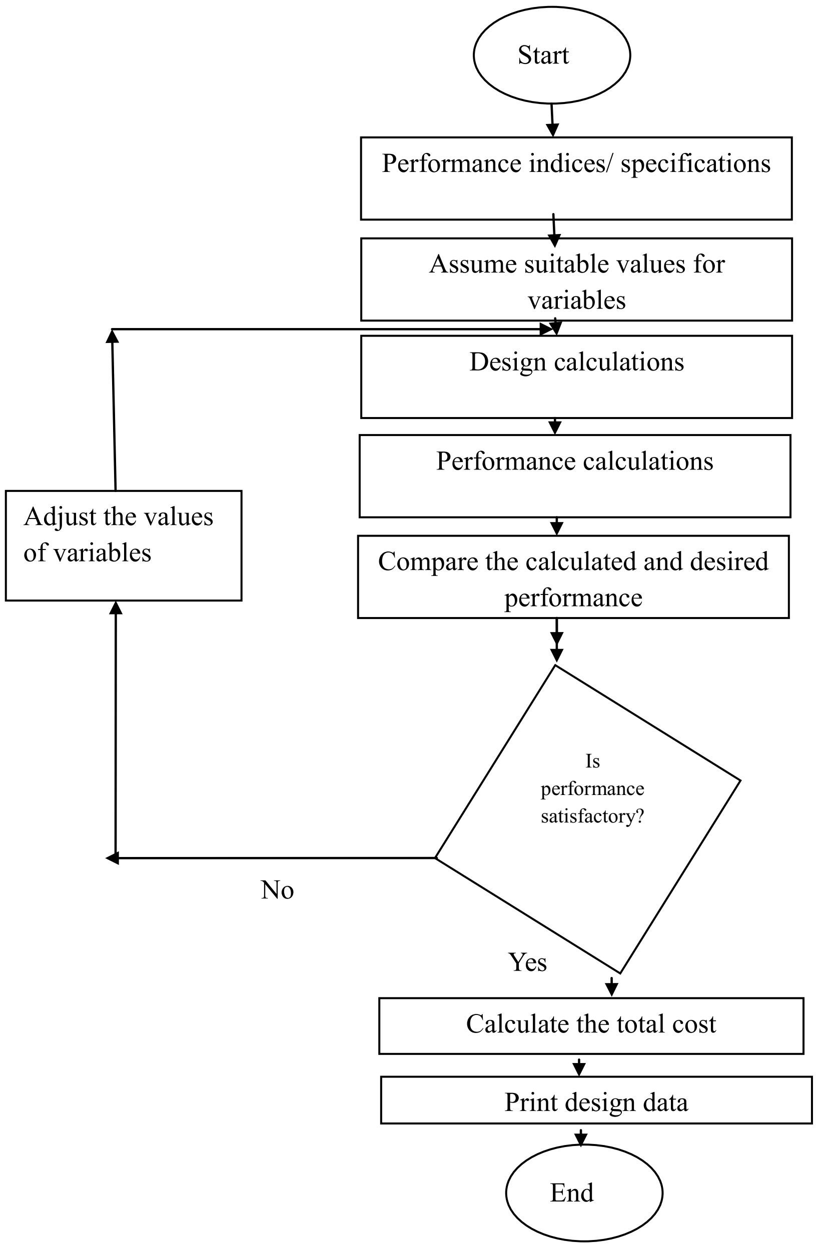
The synthesis method suffers with a number of serious disadvantages such as:-

1) This method involves too much logic since the logical decisions are left to the computer to take. Now, these logical decisions have to incorporated in the program and before, incorporation, the team of design engineers are to agree upon them.

2) The logical decisions to arrive at a optimum design are too many and then, there are too many people with too many ways to suggest to produce the optimum design and thus, it becomes really hard to formulate a logic for obtaining an optimum design.

3) The formulation of a synthesis program taking into account of factors listed would make it too complex. So, cost of computer program becomes high and thus use of a large computer and also large running time involves huge expenditure.

4) The synthesis program formulated at a high cost cannot be used for ever, as due to changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions etc., the program has to be changed and up dated keeping. Thus synthesis method requires additional efforts and cost in order for the above.



b): General procedure of optimization: The general objective of the optimization is to choose a set of values of the independent variables, subject to variousrestrictions, which will produce the desired response for the particular problem under examination. A general procedure of optimization is as under:-

1. Define a suitable objective for the problem under examination.

2. Examine the restrictions imposed upon the problem by external agencies.

3. Choose a system or systems for study.

4. Examine the structure of each system and the interrelationship of the system elements and streams.

5. Construct a model for the system. This is a technical design stage which allows the objective to be defined in terms of the system variables.

6. Examine and define the internal restrictions placed on the variables.

7. Carry out the simulation by expressing the objective in terms of the system variables, using the system model. This is the objective function.

8. Analyse the problem and reduce it to its essential features. This reduction is necessary in many cases to allow optimization to carry.

9. Verify that the proposed model represents the system being studied.

10. Determine the optimum solution for the system and discuss the nature of the optimum conditions.

11. Using the information thus obtained, repeat the procedure until a satisfactory result is obtained.

Electrical Machine Design

SOLVED QUESTION PAPER-7

Note: Attempt *Five* questions in all, selecting one question from each unit.

UNIT-I

Q. 1: a): A 50MVA, turbo-generator has a total loss of 1500kW. Calculate the volume of air required for second and also the fan power if the temperature rise in the machine is to be limited by 30^0C. The other data given is:

Inlet temperature of air = 25^0C

Barometric height = 760mm of mercury

Pressure = $2kN/m^2$

Fan efficiency = 0.4

b): Derive the expression to calculate the quantity of cooling medium required to absorb losses of machine.

Sol: a): Given that, total losses, Q = 1500kW,

Inlet temperature of air, $\theta_i = 25^0C$

Barometric height, H = 760mm of mercury

Temperature rise, $\theta = 30^0C$

Assume, specific heat of air at constant pressure and constant temperature, is $c_p = 0.995$ kJ/kg-^{0}C & volume of 1kg of air at N.T.P. is V = $0.775m^3$

So, volume of air required is, $\mathbf{V_a = 0.78\ (1500/30) \times (25+273 / 273) \times (760 / 760) = 42.6\ m^3/sec}$

$\mathbf{V_a = 0.78\ (Q / \theta) \times (\theta_i + 273 / 273) \times (760 / H)\ m^3/sec}$

or, $V_a = 0.78\ (1500/30) \times (25+273 / 273) \times (760 / 760) = 42.6\ m^3/sec$

Fan power required is, $\mathbf{P_f = P \times (V_a / \eta_f) \times 10^{-3}}$

where, η_f = fan power efficiency = 0.4

P = pressure = $2kN/m^2 = 2000\ N/m^2$

Thus,

b) Quantity of cooling medium: The quantity of cooling medium (coolant) required to absorb losses of machines can be calculated as below:

Let Q = losses to be dissipated, kW

θ_i = inlet temperature of cooling medium. ^{0}C

θ = temperature rise of cooling medium, ^{0}C

H = barometric height of mercury, mm of mercury

P = pressure, N/m^2

1. Air: Heat to be carried away = Q kW = Q x 10^3 W or J/sec

Let c_p = specific heat of air at constant pressure, J/kg – ^{0}C

As, heat = weight x sp. heat x temperature rise

&, heat per second = weight of air Kg/sec x sp. heat in J/kg -^{0}C x temperature rise in ^{0}C

So, Weight of air = $(Q \times 10^3) / (c_p \times \theta)$ kg /sec

Let volume of 1 kg air at N.T.P. (0^0C or 273^0K and 760mm of mercury) = V m^3

So, Volume of air required a N.T.P. = $[(Q \times 10^3) / (c_p \times \theta)] \times V\ m^3/sec$

Applying kelvin's law, we get, $\mathbf{(P_1 V_1 / T_1) = (P_2 V_2 / T_2)}$

Volume of air under actual working condition is,

$$\mathbf{V_a = (Q / c_p \times \theta) \times V \times (\theta_i + 273 / 273) \times (760/ H) \times 10^3\ m^3/sec}$$

The specific values of dry air are: $\mathbf{c_p = 0.2375\ cal/gm\text{-}^0C = 0.995\ kJ/ kg\text{-}^0C, V = 0.775\ m^3}$

Thus, volume of air required as cooling medium is as under:

$$\mathbf{V_a = 0.78\ (Q / \theta) \times (\theta_i + 273 / 273) \times (760/ H)\ m^3/sec}$$

2. **Hydrogen**: The specific heat of hydrogen at constant pressure is $\mathbf{c_p = 3.4\ cal/gm\text{-}^0C}$ and volume of 1Kg of dry gas hydrogen is 11.3m^3 at N.T.P. (0^0C or 273^0K and 760mm of mercury).

As per the above procedure, we get volume of hydrogen required to dissipate the heat with a temperature rise of θ^0C,

$$\mathbf{V_h = 0.8\ (Q / \theta) \times (\theta_i + 273 / 273) \times (760/ H)\ m^3/sec}$$

The value of H for hydrogen is 2000-2500mm

3. **Water**: The specific heat of hydrogen at constant pressure is $\mathbf{c_p = 1\ cal/gm\text{-}^0C = 4.18\ kJ/ kg\text{-}^0C}$. The volume of water required to dissipate the heat with a temperature rise of θ^0C,

$$\mathbf{V_w = 1000\ Q / (\theta \times 4.18) = 0.24\ Q/\theta\ litre/sec}$$

4. **Oil**: The volume of oil required to dissipate the heat of Q kW with a temperature rise of θ^0C,

$$\mathbf{V_w = 0.24\ Q/ (0.35\ to\ 0.5)\theta\ litre/sec}$$

Q. 2: a): Explain the methods used for determination of motor rating for variable load drives.

b): Explain in detail with examples and diagrams, induced and forced ventilations.

Sol: a): Methods used for determination of motor rating for variable load drives: The four commonly methods used for the determination of proper rating of the motors for variable load drives:

a) Method of average losses.

b) Equivalent current method

c) Equivalent torque method, &

d) Equivalent power method

a) Method of average losses: This method consists of finding average losses Q_{av} in the motor when it operates according to the given load diagram. These losses are then compared with Q_{nom}, the losses corresponding to the continuous duty of the machine when operated at its normal rating. The method of average losses presupposes that when $Q_{av} = Q_{nom}$, the motor will operate without temperature rise going above the maximum permissible for a particular class of insulation.

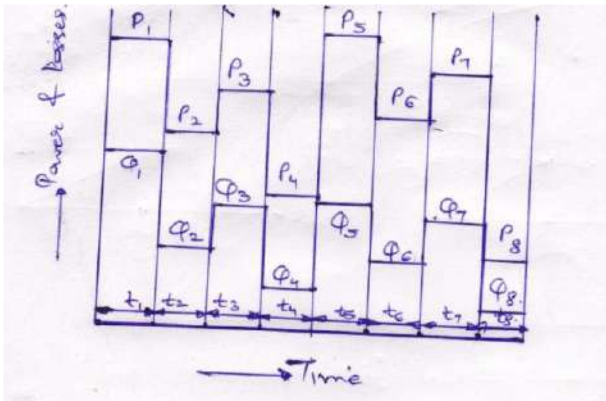
$$\theta_{per} = Q_{nom} / (S\lambda)$$

& $$\theta_m = Qav / (S\lambda)$$

$$\mathbf{\theta_m = \theta_{per} = Qav / (S\lambda) = Q_{nom} / (S\lambda)}$$

Fig. shows a simplified load diagram for a certain load drive. The loss diagram (Q versus time) of the electric motor is as shown. The rating of the motor can be found from method of successive approximations. The losses of the motor are calculated for each portion of load diagram. The average losses are given by

$$Q_{av} = (Q_1 t_1 + Q_2 t_2 + \ldots + Q_n t_n) / (t_1 + t_2 + \ldots + t_n)$$



The average losses Q_{av}, can be found from the above equation, are compared with the losses of selected motor at rated efficiency. In case, the two losses are equal or differ by a small amount, the motor is selected. However, in case, the two losses differ considerably, another motor is selected and the calculations are repeated till a motor having same amount of losses as the average losses.

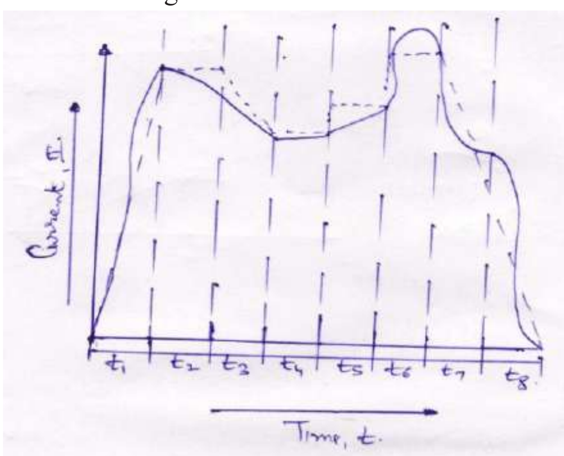
This method of average losses does not take into account of the maximum temperature rise under variable load conditions. However, this method is accurate and reliable for determining the average temperature rise of the motor during one work cycle. The disadvantage of this method is that it is tedious to work with and also many a times the efficiency curve is not readily available.

a) Equivalent current method: The equivalent current method is based upon the assumption that the actual variable current may be replaced by an equivalent current I_{eq}, which produces the same losses in the motor as the actual current. This method also assumes that the constant losses are independent of load.

$$I_{eq} = \sqrt{(I_1^2 t_1 + I_2^2 t_2 + \ldots + I_n^2 t_n) / (t_1 + t_2 + \ldots + t_n)}$$

The heating and cooling conditions in self ventilated machines depends upon the speed. At low speeds the cooling conditions are poorer than at normal speeds.

The equivalent current as found from the above equation should be compared with the rated current of the motor selected and the conditions $I_{eq} \leq I_{nom}$, should be met. The equivalent current may not be easy to calculate especially in cases where the current load diagram is irregular as shown in fig.



The above method allows the equivalent current values to be calculated with accuracy sufficient for practical purposes.

a) Equivalent Torque & Equivalent Power method: It often becomes necessary to use torque or power load diagram for the selection of motor capacity. The equivalent torque or power is found in the same manner as that of equivalent current method.

The torque is directly proportional to current and thus, the equivalent torque is:

$$T_{eq} = \sqrt{(T_1^2 t_1 + T_2^2 t_2 + \ldots + T_n^2 t_n) / (t_1 + t_2 + \ldots + t_n)}$$

The above relationship also assumes that the electromagnetic torque and the torque available at the shaft are approximately equal. The equation of equivalent power follows directly as power is proportional to torque. At constant speed or where the changes in speed are small, the equivalent power is given as under:

$$P_{eq} = \sqrt{(P_1^2 t_1 + P_2^2 t_2 + \ldots + P_n^2 t_n) / (t_1 + t_2 + \ldots + t_n)}$$

The equivalent current method is the most accurate method out of all three methods. This method may be used to determine the motor capacity for all uses except where it is necessary to take into account the changes. The equivalent torque method cannot be used for selection of motor rating for cases in which the field flux does not remains constant like d.c. series motors.

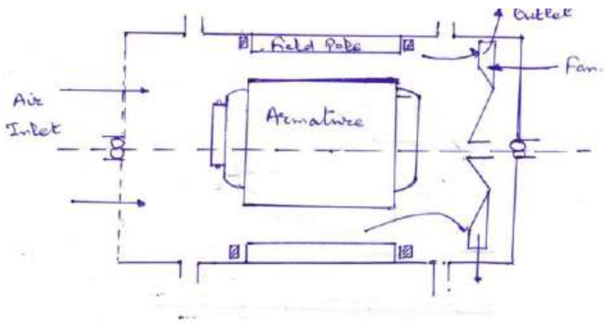
The disadvantage of equivalent power method is that it cannot be used for motors whose speed varies considerably under load, especially when starting and braking conditions are applied.

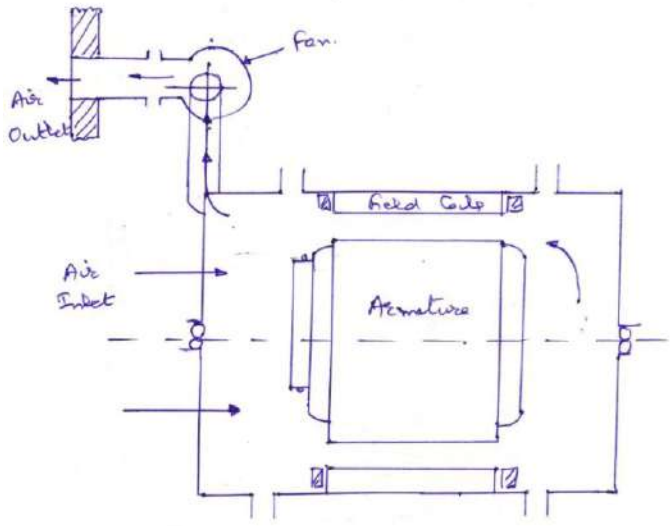
b): Induced and Forced ventilations: Both self ventilation and separate ventilation may be subdivided into two categories:

I) Induced ventilation

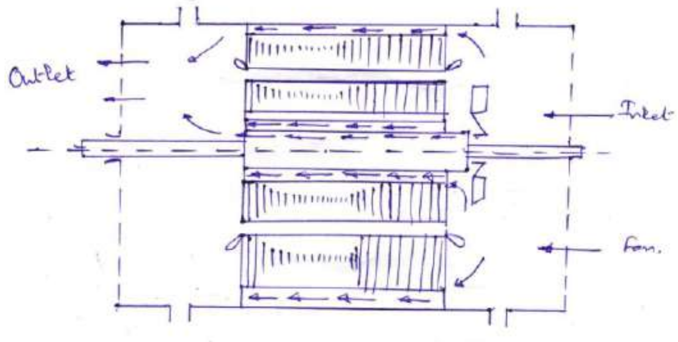
ii) Forced ventilation

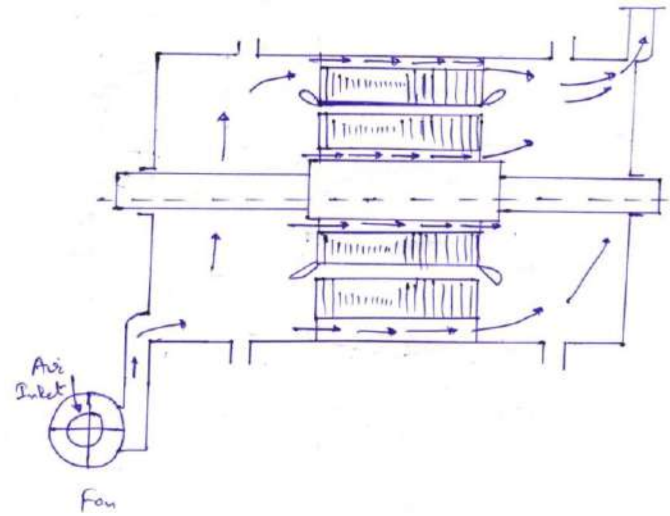
The ventilation of the machine is induced if the fan produces a decreased pressure of air inside the machine causing the air to be sucked into the machine under the external atmospheric pressure. The air is then pushed out by the fan into the atmosphere. Figs. show the induced ventilation using internal and external fans.





The ventilation of machine is said to be forced if the fan sucks the air from the atmosphere and forces it into the machine, from where it is then pushed out to the atmosphere.





Induced self ventilation is most commonly used in machines of small and medium power outputs. In this case, the built in fan is mounted on the shaft within the end shield on the driving end. In induced ventilation, cold air enters the machines whereas in forced ventilation, the temperature of cooling air rises on account of losses in the fan. Thus the amount of air required to cool the machine is higher in forced ventilation. Low noise level machines are designed with smaller specific loadings and losses per unit dissipating surface are small. This permits the use of fans with smaller diameters. In such cases, it is possible to use forced self ventilation. In induction motors having radial ducts on the stator and rotor, forced self ventilation is adopted as a rule.

UNIT-II

Q. 3: Design a single phase transformer to be connected to 230V, 50Hz supply. The transformer is to deliver 3A at 50V.

Sol: Major design problem:

Core: volt ampere rating of transformer = 50 x 3 =150VA

Primary input voltage, V_p = 230V

The starting point to design of small transformer is the choice of turns per volt. The values of turns per volt are given as under:

VA	Turns per volt	VA	Turns per volt
10	23.3	200	3.5
15	17.5	250	2.8
20	14.0	300	2.8
25	11.7	400	2.3
50	7.0	500	2.0
75	5.6	750	1.7
100	4.6	1000	1.6
150	4.0		

From the above

table, **turns per volt, $T_e = 4.0$**

Now, voltage, $E = 4.44\, f\, \Phi_m\, T$

Thus, turns per volt, $T_e = T / E = 1/4.44\, f\, \Phi_m$

or, $\mathbf{\Phi_m = 1/4.44\, f\, T_e = 1 / (4.44 \times 50 \times 4.0) = 1.125m\ Wb}$

Taking a flux density of 1.0 Wb/m^2,

Net iron area of core, $A_i = \Phi_m / B_m = 1.125 \times 10^{-3} / 1.0 = 1.125 \times 10^3\ mm^2$

Gross core section of core, $A_{gi} = A_i / K_s = 1.125 \times 10^3 / 0.9 = 1.255 \times 10^3\ mm^2$

For a small transformer, a square section is normally used for the central limb, i.e. width of core is made equal to width of central limb.

or, **width of central limb, $A = \sqrt{(A_{gi})} = \sqrt{(1.255 \times 10^3)} = 35.4mm$**

Primary winding: The efficiency of small transformer is always varies from 80 to 96% & let it is assumed to be 92%.

Primary winding current, $\mathbf{I_p = VA / (\eta\, V_p) = 150 / (0.92 \times 230) = 0.71A}$

Area of primary winding conductors, $a_p = I_p / \delta_p$, where **δ_p is the current density in the primary winding conductors in A/mm^2 and usually it is taken as $2.3/mm^2$**.

Area of primary winding conductors, $a_p = I_p / \delta_p = 0.71 / 2.3 = 0.309mm^2$

Diameter of primary winding conductor, $d_p = (a_p \times 4 / \pi)^{1/2} = 0.626mm$

Enamelled round conductors are used for windings of small transformer. Thus, the diameter of nearest bare standard conductor = 0.63mm and diameter of insulated conductor = 0.707mm.

Space factor of primary winding, $S = 0.8\, (d_{bare} / d_{insulated})^2 = 0.8\, (d / d_1)^2 = 0.8\, (0.63 / 0.707)^2$

$S_f = 0.635$

So,

Area of primary winding conductor, $a_p = (\pi / 4) \times (d_{bare})^2 = (\pi / 4) \times (0.63)^2 = 0.312mm^2$

Turns in primary winding, $T_p = V_p \times T_e = 230 \times 4.0 = 920$

Window space required for primary winding $= T_p \times a_p / S_f = 920 \times 0.312 / 0.635 = 465mm^2$

Secondary winding:

Secondary winding current, $\mathbf{I_s = VA / V_s = 150 / 50 = 3A}$

Area of secondary winding conductors, $a_p = I_p / \delta_p$, where **δ_p is the current density in the secondary winding conductors in A/mm^2 and usually it is taken as $2.3/mm^2$**.

Area of 2^0 winding conductors, $a_s = I_s / \delta_s = 3 / 2.3 = 1.3mm^2$

Diameter of 2^0 winding conductor, $d_s = (a_s \times 4 / \pi)^{1/2} = 1.285mm$

Enamelled round conductors are used for windings of small transformer. Thus, the diameter of nearest bare standard conductor = 1.32mm and diameter of insulated conductor = 1.42mm

Space factor of primary winding, $S = 0.8\,(d_{bare} / d_{insulated})^2 = 0.8\,(d / d_1)^2 = 0.8\,(1.32 / 1.42)^2$

$S_f = 0.69$

So,

Area of 2^0 winding conductor, $a_s = (\pi / 4) \times (d_{bare})^2 = (\pi / 4) \times (1.32)^2 = 1.37mm^2$

Turns in secondary winding, $T_s = 1.5 \times V_s \times T_e = 1.5 \times 50 \times 4.0 = 300$

Window space required for primary winding = $T_s \times a_s / S_f = 300 \times 1.37 / 0.69 = 595mm^2$

Stamping size:

Total window space required, $A_w = 1.2$ (window area required for 1^0 and 2^0 windings) **Width of central limb, A = 35.4mm = 1.39"**

& **area of window, $A_w = 1272mm^2 = 1.97$ sq. inch**

or, **$A_w = 1.2 \times (465 + 595) = 1272mm^2$**

Width of central limb, A = 35.4mm = 1.39"
& area of window, $A_w = 1272mm^2 = 1.97$ sq. inch

Q. 4: A 1000kVA, 3300V, 50Hz, 300rpm, 3-phase alternator has 180 slots with 5 conductors per slot. Single layer winding with full pitch coil is used. The winding is star connected with one circuit per phase. Determine the specific magnetic and electric loadings if the stator bore is 2.0m and the core length is 0.4m. Using the same loadings, determine the corresponding data for a 1250kVA, 3300V, 50Hz, 250rpm, 3-phase star connected alternator having 2 circuits per phase. The machines have 60^0 phase spread.

Sol: Given for 1000kVA star connected alternator,

kVA = 1000kVA

Input voltage, $V_L = 3300V$

f = 50Hz

synchronous speed, $N_s = 300rpm$

So, no. of poles, $P = 120 \times f / N_s = 20$

synchronous speed, $n_s = 300 / 60 = 5$ r. p. sec.

Also given, no. of conductors per slot = 5

& no. of slots = 180

Total no. of conductors, $Z = 180 \times 5 = 900$

& Turns per phase, $T_{ph} = Z / 6 = 900 / 6 = 150$

No. of slots per pole per phase, $q = 180 / (3 \times 20) = 3$

Stator bore diameter, D = 2.0m, Core length, L = 0.4m

So, distribution factor, $K_d = \sin(q\,\sigma/2) / [q \times \sin(\sigma/2\,q)]$

As given, the winding are 60^0 phase spread

So, assume, $q\sigma = 60^0$

Thus, distribution factor, K_d = Sin (60 / 2) / [3 x sin (60 /2 x 3)] = 0.96

As further given, full pitch coils are used.

Thus, pitch factor, K_p = 1

So, **winding factor, $K_w = K_d \times K_p = 0.96$**

Voltage per phase, $E_{ph} = V_L / \sqrt{3} = 3300 / \sqrt{3} = 1905V$

So, flux per pole, $\Phi_m = Eph / (4.44\, f \times K_w \times T_{ph})$

$$\Phi_m = 1905 / (4.44 \times 50 \times 0.96 \times 150) = 59.6 \times 10^{-3}\ Wb$$

Pole pitch, $\tau = \pi \times D / p = \pi \times 2.0 / 20 = 0.314m$

So, **area per pole, $A_p = \pi D L / P = \tau \times L = 0.314 \times 0.4 = 125.6 \times 10^{-3}\ m^2$**

Thus, specific magnetic loading, $B_{av} = \Phi_m / A_p = 59.6 \times 10^{-3} / 125.6 \times 10^{-3} = 0.474 Wb/m^2$

Specific magnetic loading, B_{av} = 0.474Wb/m^2

Current per phase, $I_{ph} = kVA / \sqrt{3} \times V_L = 1000 \times 1000 / \sqrt{3} \times 3300 = 175A$

Since there is only one circuit per phase,

So, **current in each conductor I_s = current per phase, 175A Specific electric loading, ac = 25066AT/m** So, specific electric loading, ac = $6 I_s T_{ph} / (\pi D) = 6 \times 175 \times 150 / \pi \times 2.0 = 25066AT/m$

Specific electric loading, ac = 25066AT/m

Peripheral speed, $v = \pi \times D \times n_s = \pi \times 2.0 \times 5 = 31.4m/sec.$

For 1250kVA generator

Given, synchronous speed, N_s = 250 rpm

or, synchronous speed, n_s = 250 / 60 = 4.167 r.p.sec.

So, **no. of poles, $p = 120 f / N_s = 120 \times 50 / 250 = 24$**

As using the same data from the above,

No. of slots per pole per phase, q = 3

& winding factor, K_w = 0.96

Thus, output coefficient, $C_o = 11 \times Bav \times ac \times K_w \times 10^{-3}$

$$C_o = 11 \times 0.474 \times 25066 \times 0.96 \times 10^{-3} = 125.5$$

So, **product, $D^2L = Q / C_o \times n_s = 1250 / 125.5 \times 4.16 = 2.39m^3$**

As given, so, peripheral speed in both the cases is same.

Thus, $v = \pi \times D \times n_s = 31.4m/sec.$

or, $D = 31.4 / (\pi \times 4.16) = 2.4m$

& $L = D^2L / D^2 = 2.39 / (2.4)^2 = 0.414m$

Diameter, D = 2.4m
& Length L = 0.414m

Now, **pole pitch, $\tau = \pi$ x D/ p = π x 2.0 / 24 = 0.314m**

Flux per pole, $\Phi = B_{av}$ x (π D L/p) = B_{av} x τ x L = 0.474 x 0.314 x 0.414 = 62 x 10^{-3} Wb

$$\Phi = B_{av} \text{ x } (\pi D L/p) = B_{av} \text{ x } \tau \text{ x } L = 0.474 \text{ x } 0.314 \text{ x } 0.414 = 62 \text{ x } 10^{-3} \text{ Wb}$$

If suppose we have more than one circuit per phase,

Let, no. of parallel paths, a =2

Voltage per phase, $E_{ph} = 4.44 f (T_{ph} / a) \Phi K_{w1}$

or, $T_{ph} = E_{ph} \text{ x } a / (4.44 f \Phi K_{w1}) = 2 \text{ x } 1905 / (4.44 \text{ x } 50 \text{ x} 0.062 \text{ x } 0.96) = 288$

$$T_{ph} = 288$$

So, **total no. of conductors, Z = 6 x T_{ph} = 6 x 288 = 1728**

& **total no. of slots = 3x p x q = 3 x 24 x 3 = 216**

& **conductors per slot = 1728 / 216 = 8**

UNIT-III

Q. 5: An induction motor frame has a large number of stator slots and a squirrel cage rotor winding. The machine can be wound for various numbers of poles. The maximum flux density, the maximum current density, the supply frequency and the supply voltages are constant.

a) Show that the magnetizing volt-ampere required for the machine are independent of number of poles.

b) Show that the rated torque output available from the machine is inversely proportional to the number of poles.

c) Show that the power conversion capability of machine is inversely proportional to the number of poles.

d) If the power factor at rated load of a 4-pole machine is 0.9, estimate the power factor at rated load if the machine is rewarded for 8-poles.

Sol:

a) & b): As the rated output torque of an induction motor is,

$$T = (k \Phi s E_2^2 R_2) / [R_2^2 + (sX_2)^2]$$

or, $T = (k \Phi s V^2 R_2) / [R_2^2 + (sX_2)^2]$ **($E_2 \alpha \Phi \alpha V$)**

or, $T \alpha (V)^2$

& Stator voltage per phase,

$$V_{ph} = 4.44 \text{ x } f \text{ x } \Phi \text{ x } K_w = 4.44 f Kw Bm \text{ x } (\pi DL /P)$$

or, $V_{ph} \alpha (1 / P)$

Thus, $\mathbf{T \alpha (1/P)^2}$

So, **the rated output torque of the machine is inversely proportional to number of poles.**

c): As the rated power output from the machine is given by,

$$Q = C_0 \text{ x } D^2 L \text{ x } n_s$$

or, $$Q = C_0 \text{ x } D^2 L \text{ x } (2 f / P)$$

So, the rated power output capability of the machine is inversely proportional to the number of poles.

Q. 6: Design a 370W, 230V, 50Hz, 4-pole single phase capacitor start induction motor. The full load efficiency and power factor should not be less than 0.65 and 0.62 respectively. The starting torque should be about 300 percent of

full load torque with starting current not over 25A. The motor is to be of open type with temperature rise of windings not above 40°C for continuous operation.

Sol: Given that, power output = 370W = 0.37kW

Input voltage, V_1 =230V

f = 50Hz

no. of poles, P = 4

So, synchronous speed, N_s = 120 f / P = 1500rpm

or, synchronous speed, n_s = 1500 / 60 = 25 r.p.sec

full load efficiency, η = 0.65

full load power factor, Cos Ø = 0.62

Watt / r.p.sec = 370 / 25 = 14.8

Thus, on the basis of above W/ r.p.sec. value, the value of (C_0 η cos Ø) is,

Values of Product C_0 η cos Ø

Watt/r.p.sec.	3.6	7.2	12	14	15	18
Product C_0 η cos Ø (m^3)	9.5	12	15.5	16.5	16.75	18

So, from the above table, the product value is 16.5.

As per output equation of induction motor,

kVA input Q = $C_0 D^2 L n_s$

& input kVA = output kW / (η x cos Ø) = 0.37 / (0.65 x 0.62) = 0.918 kVA

So, product $D^2 L$ = input kVA / ($C_0 n_s$) = output kW / (C_0 η x cos Ø x n_s)

$D^2 L$ = 0.37 / (16.5 x 25) = 0.897 x 10^{-3} m^3

Let assume for 1-phase induction motor, core length is made equal to the pole pitch,

or, take, **τ = L**

or πD /P = L

or, **L = π D / 4 = 0.785D** Put in the product equation, we get,

Put in the product equation, we get,

D = 0.1045m

Take, D = 0.109m = 109mm (As **per standard of stainless steel)L = 0.075m =75mm**So, core length, **L = 0.897 x 10^{-3} / $(0.109)^2$ = 0.075m =75mm**

L = 0.075m =75mm

Now, Pole pitch, τ = π D /P = π x 0.109 / 4 = 0.0855m

Thus,

Net iron length, L_i = K_s x L

where, K_s = stacking factor = 0.95

Thus, net iron length, **L_i = 0.95 x 0.075 = 0.07125**

Thus, total no. of stator slots, $S_s = 36$ (**standard of stainless steel**)

So, **Stator slot pitch, $Y_{ss} = \pi D / S_s = 0.0952m = 9.52mm$**

Flux per pole:

Assume width of stator tooth, $W_{ts} = 4mm = 4 \times 10^{-3}$ m

The flux density in the stator core should not exceed 1.5Wb/m^2 and generally it lies between 0.9 to 1.4Wb/m^2. So, take flux density for stator tooth, $B_{ts} = 1.1Wb/m^2$,

Flux density in stator teeth, $B_{ts} = \Phi_m / [(S_s / p) \times L_i \times W_{ts}]$ **$\Phi_m = 1.1 \times (36 / 4) \times 0.07125 \times 4 \times 10^{-3} = 2.82 \times 10^{-3}$ Wb** So, flux per pole, $\Phi_m = B_{ts} \times (S_s / p) \times L_i \times W_{ts}$

$$\Phi_m = 1.1 \times (36 / 4) \times 0.07125 \times 4 \times 10^{-3} = 2.82 \times 10^{-3} \text{ Wb}$$

Stator Winding:

As, total no. of stator slots, $S_s = 36$ No. of poles, P = 9

Total no. of stator slots per pole = 9

As, stator induced voltage, $E = 4.44 f \Phi_m T_m K_{wm}$

where, T_m = no. of turns of main winding

K_{wm} = winding factor for main winding = 0.75 to 0.85 (**Take 0.8**)

Stator induced voltage E ≈ 95% of supply voltage = 0.95 x 230 = 218.5V$T_m = E / (4.44 f \Phi_m K_{wm}) = 218.5 / (4.44 \times 50 \times 2.82 \times 10^{-3} \times 0.8) = 436$

So, no. of turns of main winding,

$$T_m = E / (4.44 f \Phi_m K_{wm}) = 218.5 / (4.44 \times 50 \times 2.82 \times 10^{-3} \times 0.8) = 436$$

Number of turns in series per pole for main (running) winding,

$T_{pm} = T_m / P = 436 / 4 = 109$

Conductor size:

Current in the main winding, $I = W / (V \eta \cos Ø)$

$I = 370 / (230 \times 0.65 \times 0.62) = 4A$

Area of running conductor in main winding, $a_m = I / \delta_m$

where, δ_m is current density for running winding conductors in A/mm^2.

For open type split phase, capacitor start and repulsion start motor, the current density can be 3 to 5A/mm^2. (**Take 4.8 A/mm^2 for this problem**).

Area of running conductor in main winding,

$$a_m = I / \delta_m = 0.833mm^2$$

Diameter of bare conductor, $d = \sqrt{am / (\pi/4)} = 1.02mm$

Diameter of insulation used for the above conductor = 0.063mm (**As per standard**)

So, **Total diameter of insulated conductor = 1.02 + 0.063 = 1.083mm**

Length of mean turn: Length of mean turn,

$L_{mt} = [8.4 \times (D + d_{ss}) / S_s] \times \text{slots spanned} + 2L$

or, $L_{mt} = (8.4 \times (0.109 + 0.019) / 36] \times 5 + 2 \times 0.075 = 0.321m$

Rotor Design:

Length of air gap: The empirical formula is,

Gap length, $\mathbf{l_g = 0.007 \times rotor\ diameter / \sqrt{p} = 0.007 \times 0.109 / \sqrt{4} = 0.38mm}$

Number of rotor slots: Useful rule for selecting the number of rotor slots is that the number of rotor slots should be equal to number of stator slots plus twice the number of poles. The number of rotor slots must also be selected from the point of view of magnetic locking.

So, number of rotor slots, $\mathbf{S_r = S_s + 2 \times p = 36 + 2 \times 4 = 44}$

Area of rotor bars:

Total cross-section of rotor bars, $A_b = S_r \times a_b$

where, a_b = area of each rotor bar, mm^2

So, a_b = area of each rotor bar = $20mm^2$

Thus, total cross-section of rotor bars, $A_b = S_r \times a_b = 44 \times 20 = 880mm^2$

& total stator copper section for main winding, $A_m = 2\, T_m\, a_m = 2 \times 436 \times 0.833 = 726mm^2$

Ratio, $A_r / A_m = 880 / 726 = 1.21$

Area of end rings:

End ring current, $I_e = S_r I_b / (\pi \times p) = 44 \times 4 / (\pi \times 4) = 14.00$

Area of each end ring, $a_e = I_e / \delta_e = (0.32\, A_r / p) \times (\delta_b / \delta_e)$

\$a_e = (0.32 \times 880/ 4) = 70.4mm^2$ (take $\delta_b = \delta_e$)

diameter of end ring, $d_e = \sqrt{a_e / (\pi/4)} = 96mm$

Resistance of main winding: Resistance of running winding,

$r_{sm}\,(hot) = 0.021 \times (T_m L_{mtm} / a_m)$

where, L_{mtm} = length of mean turn of main winding, m

a_m = area of running winding, m^2

$\mathbf{r_{sm}\,(hot) = 0.021 \times (436 \times 0.321 / 0.833) = 3.52\Omega,}$ **at 75^{0}C**

$r_{sm}\,(cold) = 0.017 \times (T_m L_{mtm} / a_m)$

$\mathbf{r_{sm}\,(cold) = 0.017 \times (436 \times 0.321 / 0.833) = 2.85\Omega,}$ **at 20^{0}C**

Resistance of rotor winding: Rotor resistance referred to running winding,

$r_{rm}' = 8\, T_m^{\ 2} K_{wm}^{\ 2} \rho\, [L_b / (S_r a_b) + (2 / \pi) \times (D_e / p^2 \times a_e) \times K_{ring}]$

where, $L_b = \sqrt{(L)^2 + (Y_{ss})^2} = \sqrt{(75)^2 + (9.52)^2} = 75.6mm = 0.0756m$

K_{wm} = winding factor, varies between 0.75 to 0.85 (**take 0.8**)

ρ = resistivity = 0.021 Ω/m

Take, $K_{ring} = 0.96$

So, by putting all the above values as,

$r_{rm}' = 8 \times (436)^2 \times (0.8)^2 \times 0.021 \times [0.0756 / (44 \times 20) + (2 / \pi) \times (0.096/ (4)^2 \times 70.4) \times 0.96]$

$\mathbf{r_{rm}' = 2.82\Omega}$ **at 75^{0}C** $\mathbf{r_{rm}' = 2.82\Omega}$ **at 75^{0}C**

$\mathbf{r_{rm}' = 2.28\Omega}$ **at 20^{0}C&** $\mathbf{r_{rm}' = (0.017 / 0.021) \times 2.82 = 2.28\Omega}$ **at 20^{0}C**

$r_{rm}' = 2.82\Omega$ at 75^0C

$r_{rm}' = 2.28\Omega$ at 20^0C

Design of starting winding:

No. of turns on the starting (auxiliary) winding,

$$T_a = (K_{wm} / K_{wa}) \times (E_m / E_a) \times T_m$$

where, K_{wm} = main winding factor = 0.8

K_{wa} = winding factor for auxiliary winding = 0.85

& $E_m / E_a = K \approx 1.53$

So, $T_a = (K_{wm} / K_{wa}) \times (E_m / E_a) \times T_m = (0.8 / 0.85) \times 1.53 \times 436 = 628$

$T_a = 628$

Number of turns in series per pole for auxiliary (starting) winding,

$$\mathbf{T_{pa} = T_a / P = 628 / 4 = 157}$$

Note: The above pointed out standards have been taken from chapter no. 10 (Design of 3-phase induction machines) and chapter 12 (Design of 1-phase induction motors) as mentioned in the book, **"A Course in Electrical Machine Design"** by A.K. Sawhney, stating therein different standards used by the Indian industries.

Readers are advised to read these concepts thoroughly.

UNIT-IV

Q. 7: a): Explain general procedure of optimization.

b): Explain synthesis method for machine design.

Sol: a): General procedure of optimization: The general objective of the optimization is to choose a set of values of the independent variables, subject to various restrictions, which will produce the desired response for the particular problem under examination. A general procedure of optimization is as under:-

1. Define a suitable objective for the problem under examination.

2. Examine the restrictions imposed upon the problem by external agencies.

3. Choose a system or systems for study.

4. Examine the structure of each system and the interrelationship of the system elements and streams.

5. Construct a model for the system. This is a technical design stage which allows the objective to be defined in terms of the system variables.

6. Examine and define the internal restrictions placed on the variables.

7. Carry out the simulation by expressing the objective in terms of the system variables, using the system model. This is the objective function.

8. Analyse the problem and reduce it to its essential features. This reduction is necessary in many cases to allow optimization to carry.

9. Verify that the proposed model represents the system being studied.

10. Determine the optimum solution for the system and discuss the nature of the optimum conditions.

11. Using the information thus obtained, repeat the procedure until a satisfactory result is obtained.

b): Synthesis Method: The synthesis method is as depicted in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

The greatest advantage of synthesis method is as the saving in time in lapsed time and in engineering man hours on account of the decision left to the computer itself.

The synthesis method suffers with a number of serious disadvantages such as:-

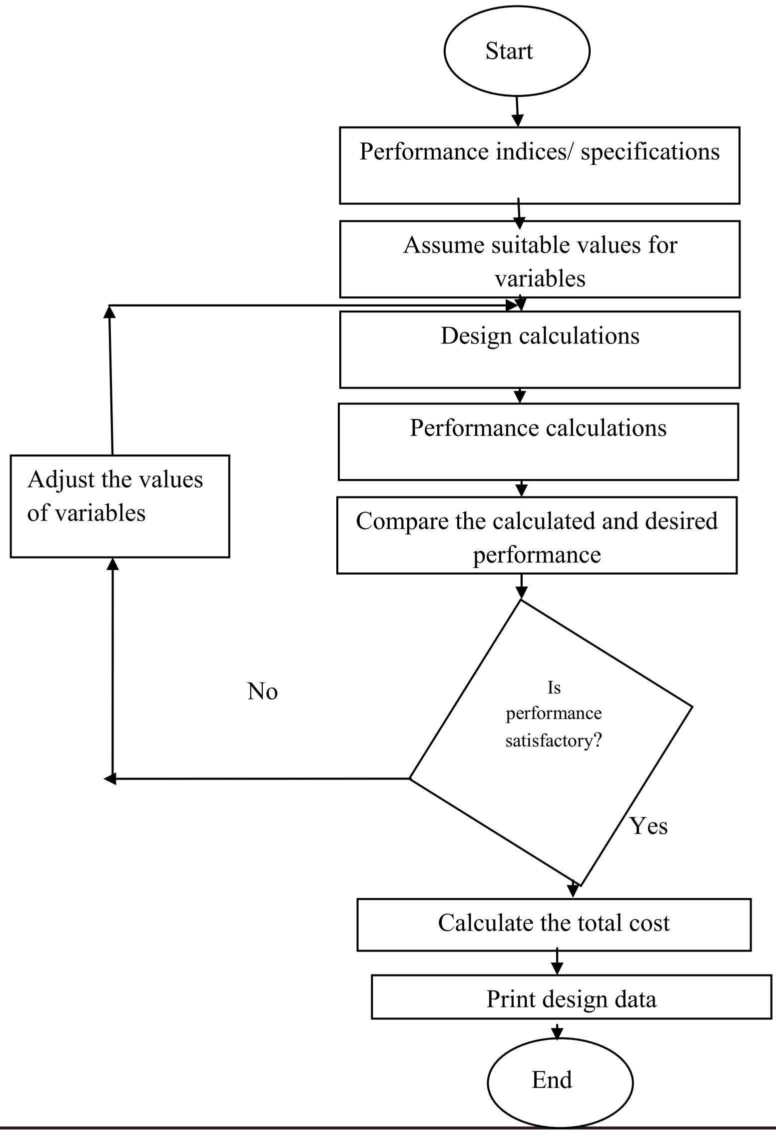
1) This method involves too much logic since the logical decisions are left to the computer to take. Now, these logical decisions have to incorporated in the program and before, incorporation, the team of design engineers are to agree upon them.

2) The logical decisions to arrive at a optimum design are too many and then, there are too many people with too many ways to suggest to produce the optimum design and thus, it becomes really hard to formulate a logic for obtaining an optimum design.

3) The formulation of a synthesis program taking into account of factors listed

would make it too complex. So, cost of computer program becomes high and thus use of a large computer and also large running time involves huge expenditure.

4) The synthesis program formulated at a high cost cannot be used for ever, as due to changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions etc., the program has to be changed and up dated keeping. Thus synthesis method requires additional efforts and cost in order for the above.



Q. 8: Write short notes on the following:

a): Development of computer program for machine design.

b): Explain performance predictions with reference to Computer Aided design.

Sol: a): Development of computer program for machine design: The application of digital computers to the problem of electrical machine design was first introduced in 1950. In the early stage, the use of digital computers for design of electrical machines was limited to design of transformers. In the year 1956, Moore and Williams discussed the applications of digital computers to the design of transformers as well as for design of rotating machines.

In the same year, Veinatt published a research of application of digital computers for the design of induction motors. A flow chart was developed giving basic procedure for the design of polyphase induction motor. The input data consisted of machine specifications alongwith the complete dimensions of stator and rotor bad the output data gave performance details. This paper in fact developed the analysis method for the design of polyphase induction motor.

The concept of optimization in electrical machine design was introduced by Godwin in 1959 and a program was developed for design of squirrel cage induction motors. The program eliminates a large number of non-useful combinations of design parameters. In 1959, Heroz introduces the concept of two commonly acceptable approaches to machine design, namely:

i) Analysis method, **ii)** Synthesis method

b): Performance predictions: The numerical quantities for which values are to be chosen in producing a design are called “design variables”. The objective function 'Y' is expressed in terms of the independent variables v, where v represents all the variables, $v_1, v_2, \ldots\ldots\ldots\ldots\ldots, v_n$ as

$$Y(v) = Y(v_1, v_2, \ldots\ldots\ldots\ldots\ldots, v_n)$$

subject to in restrictions, generally termed as Constraints, of the form,

$$g_i(v) = 0$$

or

$$g_i(v) \leq 0$$

Here, $g_i(v)$ can be variable or a function.

The sole considerations are mathematical and the optimization techniques are determined by the mathematical structures of the objective function and the associated restrictions.

SOLVED QUESTION PAPER-7

Note: Attempt *Five* questions in all, selecting at least one question from each unit. All questions carry equal marks. Assume any missing data if required.

UNIT-I

Q. 1: Discuss the factors which are to be considered for the design of "Length of air gap" & "Number of armature slots" in a d.c. machine.

Sol:

Length of air gap: The length of air gap can be fixed by considering the following factors:

i) Armature reaction: In order to prevent excessive distortion of field form by the armature reaction, the field mmf must be large in comparison with the armature mmf. A machine designed with a long air gap require large field mmf. Thus the distorting effect of armature reaction can be reduced if the length of air gap is made large. However, with the increase in field mmf, the cost and size of machine increases.

ii) Circulating Currents: The air gap, in case of lap winding machines, should be long. However if the air gap is small, a slight irregularity in air gap increase the circulating currents.

iii) Pole face losses: If the length of air gap is made large, the variations in air gap flux density due to slotting are small. Thus, pulsation losses decreases if the large air gap length is made.

iv) Noise: The operation of machine with large air gap lengths is comparatively noiseless and quiet.

v) Cooling: Large air gap lengths means better ventilation of the machine.

vi) Mechanical considerations: Initially, the machines were made up with larger air gap lengths, in order to reduce the distortion effect of field form. But now with the use of commutating poles made with the main field poles brought down the value of air gap lengths. Thus the distortion of field form has been reduced. But the use of commutating poles has also brought down the values to minimum extent keeping mechanical point of view.

Estimation of Air Gap Length:

Mmf required for air gap of salient pole machines, $AT_g = 800,000\ B_g K_g l_g$

& armature mmf per pole, $AT_a = ac \times \tau / 2$

The value of gap mmf is 0.5 to 0.7 times of armature mmf. The usual value is taken as 0.55.

So, $AT_g = (0.5 \text{ to } 0.7) AT_a = (0.5 \text{ to } 0.7)\ ac \times \tau / 2$

On solving the above equations, we get,

$$lg = (0.5 \text{ to } 0.7)\ ac \times \tau / 1600,000\ B_g K_g$$

The gap contraction factor, K_g may be assumed to be 1.15.

Usually the values of air gap length lies between 0.01 to 0.015 of pole pitch.

Number of Armature slots: The following factors should be considered when selecting the number of armature slots in d.c. machines:

i) Mechanical considerations: For a larger number of slots, the slot pitch becomes smaller and consequently the width of tooth gets smaller. This may lead to difficulties in construction for the reason that it will be difficult to support the teeth at the ventilating ducts.

ii) Slot Pitch: The value of slot pitch lies between 20 to 40mm as extreme limits. The usual limit is between 25 to

35mm except in case of very small machines, where it may be 20mm and ever less.

iii) Slot loading: The slot loading i.e. number of ampere conductors per slot should not exceed about 15000A.

iv) Cooling of armature conductors: For larger no. of slots, the number of conductor per slot is less and so, only a few conductors are bunched together. Thus, the cooling of armature conductors is better if a larger number of slots are taken,

v) Flux pulsation: The flux pulsations i.e. the changes in the air gap flux due to slotting, give rise to eddy current losses in the pole faces and produce magnetic noise. With larger no. of slots, the flux pulsations are reduced and thus there is a reduction in pole face losses and in the noise level of the machine. So, the pulsations and oscillations of air gap flux are reduced to minimum when

i) the number of slots under the pole shoe is equal to an integer plus 1/2.

ii) the number of slots per pole is equal to an integer plus 1/2.

Thus, generally the slots under one pole shoe are an integer while the slots per pole are equal to an integer plus 1/2.

vi) Commutation: Pulsations and oscillations of the flux under the interpole must be avoided, as they cause sparking. A large air gap under the interpole and a large number of slots helps to reduce the effect of slotting upon the flux under the interpole.**$(1-\psi)$ x slot per pole ≥3**In fact, the number of slots in the region of two adjacent poles should be at least 3.

or, **$(1-\psi)$ x slot per pole ≥ 3**

Take, $\psi = 0.67$,

Number of slots per pole > 9.1

So, from the above point of commutation, the number of slot per pole should be at least equal to 9. **So, for machines, the number of slot per pole usually lies between 9 to 16**.

I) Suitability for winding: When selecting the number of slots, it must confirm that the number selected suits the armature winding as regard to total number of coils and the coil sides per slot.

The number of slots per pole should not be less than according to the power ratings of the machine.

Rating	Slots per pole
Upto 5kW	8
5kW to 50kW	10
50kW and above	12 and above

Dc. windings are always 2-layer type. Thus the number of slots should be so chosen that the number of conductors per slot is an even integer. Also the number of conductors per slot should be such that they are divisible by the number of coil sides per slot.

i) Cost: A smaller number of slots are desirable considering the cost as the charges for punching the slots increases with their number. Further the smaller number of slots, there are fewer slots to insulate and thus cost of machine reduces.

Q. 2: Derive the temperature rise time curve for rotating electrical machines. Discuss the cooling of turbo-generators.

Sol: Temperature –rise time relation: When an electrical machine is switched on and put up on load, the temperature to start with rises at a rate determined by losses. As the temperature rises, the active parts of the machine and various surfaces start transferring and dissipating the heat. The higher the rise in temperature, greater is the heat dissipation. So with rise in temperature, the rate falls because of increased dissipation making the temperature-rise time curve an exponential in nature.

Assumptions: i) The machine can be considered as a homogenous body developing heat internally at uniform rate.

ii) The rate of heat transfer is proportional to the temperature difference.

Let, Q = Power loss or heat developed in the machine, W or J/sec

G = weight of active parts of the machine, Kg

c_p = specific heat, J/ kg-^{0}C

s = cooling surface, m^2

λ = specific heat dissipation, W/m^2-^{0}C

C= cooling coefficient = $1/\lambda$

θ = temperature rise at any time t, ^{0}C

θ_m = Final steady temperature rise, ^{0}C (under heating condition)

t = time, sec. / hr.

τ_h = Heating time constant, sec. / hr.

Θ_c = Final steady temperature rise, ^{0}C (under cooling condition)

τ_c = cooling time constant, sec. /hr.

Machine under Heating (Heating Cycle): Consider a situation in a machine at any time 't' from the start and a specific short time 'dt', a small temperature rise 'dθ' takes place.

So, Heat developed during the small interval = Q dt

Heat stored = weight x sp. heat x temp. difference = $G\, c_p\, d\theta$

& let the temperature of surface raises from θ over the ambient medium, then,

Heat dissipated = sp. heat dissipation x surface area x temp. rise x time = $\lambda\, s\, \theta\, dt$

According to heat balance equation,

Heat produced = heat stored + heat dissipated

or $Q\, dt = G\, c_p\, d\theta + \lambda\, s\, \theta\, dt$

or $(Q - \lambda\, s\, \theta)\, dt = G\, c_p\, d\theta$

or $dt = d\theta / [(Q/G\, c_p) - (\lambda\, s / G\, c_p)]$

On integration, we get

$$\mathbf{t = -(G\, c_p / \lambda\, s) \log_e [(Q/G\, c_p) - (\lambda\, s / G\, c_p)\theta] + k}$$

where, k = constant and can be find from the initial conditions at t=0 sec., $\theta = \theta_i$.

$$\mathbf{k = (G\, c_p / \lambda\, s) \log_e [(Q/G\, c_p) - (\lambda\, s / G\, c_p)\theta_i]}$$

So, time,

$$t = \mathbf{-(G\, c_p / \lambda\, s) \log_e [(Q/G\, c_p) - (\lambda\, s / G\, c_p)\theta] + (G\, c_p / \lambda\, s) \log_e [(Q/G\, c_p) - (\lambda\, s / G\, c_p)\theta_i]}$$

or $$\mathbf{t = -(G\, c_p / \lambda\, s) \log_e [((Q/\lambda\, s) - \theta) / ((Q/\lambda\, s) - \theta_i)]}$$

Now, at $t = \infty$, $\theta = \theta_m$ = Final steady temperature and thus there is no further increase in temperature, i.e. $d\theta = 0$.

Thus, heat production = heat dissipated (or heat stored = $G\, c_p\, d\theta = 0$)

$Q\, dt = \lambda\, s\, \theta_m\, dt$

or, $$\boxed{\theta_m = Q / \lambda\, s}$$

So, $t = -(G\, c_p / \lambda\, s) \log_e [(\theta_m - \theta) / (\theta_m - \theta_i)]$

The term, $G\, c_p / \lambda\, s$ = heating time constant, τ_h.

So, $t = -\tau_h \times \log_e[(\theta_m - \theta)/(\theta_m - \theta_i)]$

$$[(\theta_m - \theta)/(\theta_m - \theta_i)] = e^{(-t/\tau h)}$$

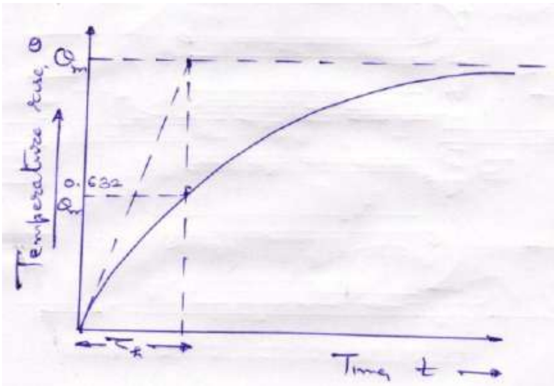
On solving the above equation, we get,

$$\Theta = \theta_m \times [1 - e^{(-t/\tau_h)}] + \theta_i \times e^{(-t/\tau_h)}$$

If the machine starts from the cold conditions, then $\theta_i = 0^0$C and

$$\Theta = \theta_m \times [1 - e^{(-t/\tau_h)}]$$

Thus, temperature-rise time curve is exponential in nature as shown:



Temperature rise-time curve

Methods of cooling of turbo-generators: The problem of cooling of turbo-generators is one of the mosr complex problems in electrical engineering since being high speed machines, their dimensions are much smaller. The various method of cooling of turbo-generators are as under:-

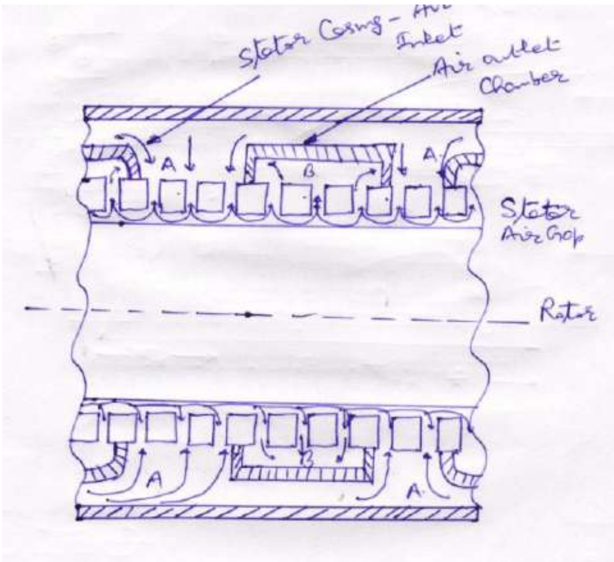
1. **Air Cooled Turbo-alternators**: The cooling of turbo-alternators by air is used for small units. The gas turbine generators rated at 17.5MW, 25MW and 35MW in large power stations are air cooled machines. Also there are a number of 30MW and 60MW air cooled machines which are in service. The following methods used for air cooling of turbo-generators are:-

a). **One sided Axial ventilation**: Machines for power outputs upto 3MW permit the use of one sided parallel axial ventilation. In this method, the machine is supplied with air by propeller fan and the air enters the machine from one side and leaves from the other side. The disadvantage of this method in long machines is the great difference in the temperature rise of the winding along the length of the machine.

b) **Two sided axial ventilation**: In this method, the air is forced through the machine from both the sides. **The two sided system of ventilation has the advantage that the end windings on both sides of machine have the same temperature rise**. The method can be used for the machines upto rating of 12MW.

c) **Multiple Inlet system**: The above two methods of axial ventilation systems cannot be used for turbo-generators having long core lengths, because the central part of these machines have not sufficient amount of air for proper cooling and thus the air reached at the central part of machine becomes hotter. So, in large machines, multiple inlet systems are adopted for their cooling.

In a multiple inlet system, the outer stator casing is divided into a number of compartments, these being used alternatively for inlet and outlet chambers as shown in fig. In the inlet chamber the air is directed radially inwards while in outlet chambers the air is directed radially outwards. Air is forced under pressure into the stator casing where it enters the inlet chamber A from where it flows radially inwards from the stator ducts and part of air passes through the axial ducts, the remaining air passes through the air gap It then passes radially outwards in the adjacent sections of the core to the outlet chambers as at B. This method can be used for machines of rating upto 60MW.



Multiple Inlet System

1. **Hydrogen Cooled Turbo-alternators**: As the capacity of turbo-generators is increased, the problem associated with the air ventilation has also increased due to requirement of large fan power and requisite quantity of air through the machine for its circulation. Thus on the above facts and circumstances, another method of cooling is needed as the rating/ capacity of machines increases. This method is hydrogen,

Hydrogen when mixed with air forms an explosive mixture over a wide range (4% to 75%) of hydrogen in air. Thus, the frame of hydrogen cooled machines has to be made strong enough to withstand possible internal explosion without serious damage. All joints in hydrogen cooling circuits are made gas tight and oil film shaft seals are used to prevent leakage of hydrogen. The seals must accommodate axial expansion of the rotor shaft and stator frame. The oil that flows towards the air mixes with air, while the oil that goes towards hydrogen is collected and degassed.

The risk of explosion in the machine casing are reduced by maintaining the hydrogen above atmospheric pressure so that any leakage from the machine to atmosphere where the hydrogen can be quickly dissipated. The pressure of hydrogen made to 200-300kN/m^2 in the modern turbo-alternators.

Fans mounted on the rotor shaft circulate hydrogen through the ventilating ducts and internally arranged hydrogen gas coolers. The gas pressure is maintained by an automatic regulating valve controlling the supply from gas coolers. When filling and emptying the casing of the machine with hydrogen, the air is first displaced with carbon dioxide gas before the hydrogen is admitted. The process is revered while emptying the machine. The purity of hydrogen is checked by measuring its thermal conductivity.

2. **Direct Cooled Turbo-alternators**: Conventionally cooled machines dissipate their losses to a coolant which is entirely outside the coil insulation. But now the direct cooling is preferred in the turbo-alternators. Direct cooling is the process of dissipating the armature and field winding losses to a cooling medium circulating within the winding insulation wall. Machine cooled in this manner is called "supercharges", "inner cooled" or "conductor cooled". In this method the coolant either is in direct contact with conductor copper or is separated only by the materials having negligible thermal resistance.

Turbo-alternators of the highest possible ratings are likely to use hydrogen cooled stator core and direct water cooled stator and rotor windings. The resistivity and hence effectiveness of water as a coolant depends upon its purity. The resistivity of water should not be less than 2000 Ωm. So, plants must be installed to provide the distilled water. Connection of water pipes, which are at earth potential, with the high tension armature are made using plastic tubing known as polytetrafluroethylene for this purpose.

An inlet seal is attached to the non-coupling end of rotor to enable the water to enter the bore of the shaft. Water travels axially to a point on the plane of overhang, where its flow becomes radial into manifolds. Water enters at the coil ends and leaves at the midpoint of each coil side. The water outlet is a simple box that surrounds the shaft. Water can be circulated through the holes in the slot wedges which are used as damper windings in a turbo-alternator. The maximum water temperatures used are of the order of 60^0 to 70^0C. These temperatures are based on a cooling water temperature not exceeding 40^0C at the many rear water inlets. The highest temperature rise of water flowing through the copper is thus, only 30^0C. The water pumping pressure is 300 kN/cm^2 and the velocity of water hardly exceeds 1.5m/sec. The maximum permissible speed of water flow is 2.5m/sec. The speed is kept low in order to avoid erosion and cavitation.

UNIT-II

Q. 3: For transformers discuss:

a) Design of Core section.

b) Design of cooling tubes.

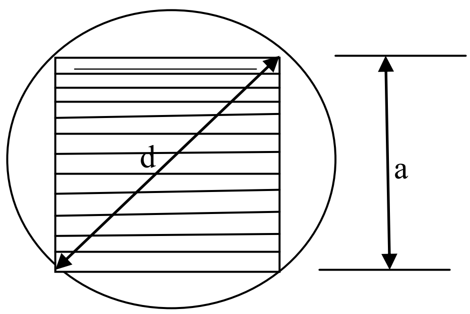
Sol: Design of Core section of transformer: The core section for the core type transformers may be rectangular, square or stepped. Shell type transformers use core with rectangular cross-section.

Rectangular Core: For core type transformers and small power transformer for moderate and low voltage, the rectangular shaped core section may be used. The ratio of depth to width of core varies between 1.4 to 2.0. Rectangular shaped coils are used for rectangular core.

For shell type transformer width of central limb is 2 to 3 times the depth of core.

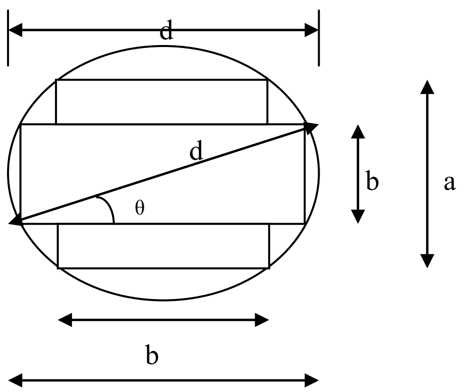
Square and Stepped core: When circular coils are required for high voltage distribution and power transformers, square and stepped cores are used. Circular coils are preferred because of their superior mechanical characteristics. A transformer coil, under mechanical stresses produced by excessive leakage flux due to short circuits, tends to assume a circular form.

With core type transformers of small sizes, simple rectangular core can be used with either circular or rectangular coils. As the size of the transformers increases, it becomes wasteful to use rectangular cores and thus, square shaped cores are preferred, as shown.



The circle represents the inner surface of the tubular form carrying the windings. This circle is called as **circumscribing circle**. In this method, the length of circumference of circumscribing circle being large in comparison with its cross-section. This means that the length of mean turn of winding is increased giving rise to higher I^2R losses and conductor costs.

With large transformers, **cruciform core**, which utilizes the space better as compared to square and rectangular cores, are used as shown under. Thus in this case, the length of circumference of circumscribing circle is smaller than square core of same area. Thus the length of mean turn of winding is reduced and thus reduction in the cost of copper. It is as shown that two different sizes of silicon steel laminations are used in cruciform cores



Cruciform Core

With large transformers, further more steps are introduced to utilize the core space which reduces the length of mean turn with consequent reduction in both the cost of core and copper losses. However, with more number of steps with reduction in the cost of winding, a large number of sizes of laminations have to be used. This results in higher labour charges for shearing and assembling different types of laminations. Thus this causes extra labour cost and extra balancing is required.

Considerations for the various types of core design:

1. **Square Core**: As per the above figure of square core,

Gross area of iron core, $A_{gi} = a^2 = (0.71d)^2 = 0.5\, d^2$

where, a = side of the square and d = diameter of circumscribing circle

Net iron area, A_i = stacking factor x gross area of core = $K_s \times A_{gi}$

or, $\mathbf{A_i = 0.9 \times 0.5d^2 = 0.45\, d^2}$ (Take $K_s = 0.9$)

$$\text{Ratio} \quad \frac{\text{Net iron area}}{\text{Area of circumscribing circle}} = \frac{0.45\, d^2}{(\pi/4)\, d^2} = 0.58$$

$$\text{Ratio} \quad \frac{\text{Gross iron area}}{\text{Area of circumscribing circle}} = \frac{0.5\, d^2}{(\pi/4)\, d^2} = 0.64$$

2. **Stepped Core**: As per the above figure of 2-stepped core of a cruciform core, the dimensions of the two steps to give maximum area for a given diameter are determined as below.

Gross area of iron core, $A_{gi} = ab + b(a - b) = 2ab - b^2$

where, $a = d\cos\theta$ and $b = d\sin\theta$

So, $A_{gi} = 2d^2 \sin\theta\cos\theta - d^2\sin^2\theta = d2(\sin 2\theta - \sin^2\theta)$

Differentiating the above equation w.r.t. θ, we get,

$$d(A_{gi})/d(\theta) = d^2(2\cos 2\theta - 2\sin\theta\cos\theta) = d^2(2\cos 2\theta - \sin 2\theta)$$

Equating, $d(A_{gi})/d(\theta) = 0$, the value of θ which gives the maximum area is found out,

$d^2(2\cos 2\theta - \sin 2\theta) = 0$ or $\tan 2\theta = 2$ or $\theta = 31.47^0\ (31^0, 45')$

So, $a = d\cos\theta = d\cos(31.47) = 0.85d$ and $b = d\sin\theta = d\sin(31.47) = 0.53d$

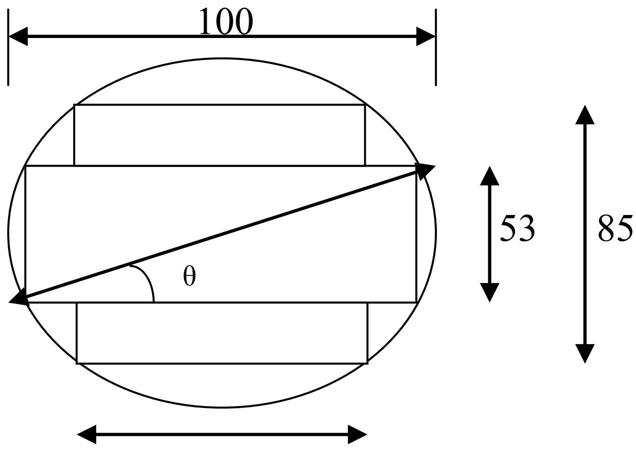
Thus, **Gross area of iron core, $A_{gi} = ab + b(a - b) = 2ab - b^2 = 0.618\, d^2$**

Net iron area, A_i = stacking factor x gross area of core = $K_s \times A_{gi}$

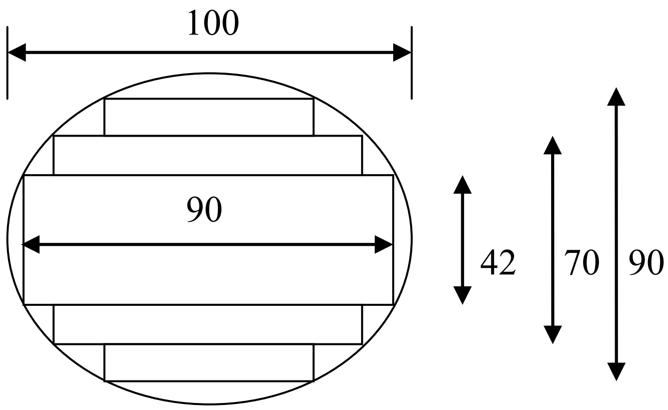
or, $\mathbf{A_i = 0.9 \times 0.618d^2 = 0.56\, d^2}$ (Take $K_s = 0.9$)

$$\text{Ratio} \quad \frac{\text{Net iron area}}{\text{Area of circumscribing circle}} = \frac{0.56\, d^2}{(\pi/4)\, d^2} = 0.71$$

$$\text{Ratio} \quad \frac{\text{Gross iron area}}{\text{Area of circumscribing circle}} = \frac{0.618\, d^2}{(\pi/4)\, d^2} = 0.79$$

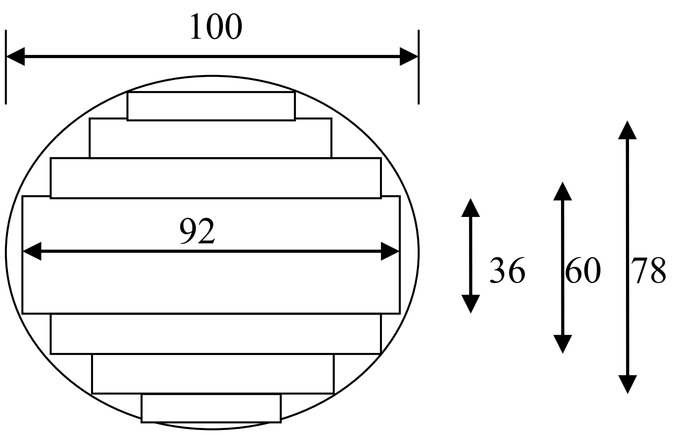


3. 3- Stepped Core: As per the above figure of 3-stepped core of a cruciform core:-



Net iron area, A_i = 0.60 d^2

4. 4- Stepped Core: As per the above figure of 4-stepped core of a cruciform core:-



Net iron area, A_i = 0.62 d^2

By increasing the number of steps, the area of circumscribing circle is more effectively utilized.

Calculation of core area: The voltage per turn is calculated as,

$$E_t = K\sqrt{Q}$$

A suitable value of K can be chosen and thus E_t can be determined.

Type	K
1-phase shell type transformer	1.0 to 1.2
1-phase core type transformer	0.75 to 0.85
3-phase shell type transformer	1.3
3-phase core type transformer (distribution)	0.45
3-phase core type transformer (power)	0.6 to 0.7

Now, flux, $\Phi_m = E_t / (4.44\, f)$

Now, core area required, $\mathbf{A_i = \Phi_m / B_m}$

& gross core area, $\mathbf{A_{gi} = A_i / K_s}$

Choice of flux density: The value of flux density in the core determines the core area. Higher values of flux density give a smaller value of core area and so, there is a saving in the cost of iron. Also the length of mean turn of winding is also reduced. Thus the conductor cost is also reduced. But the iron losses become reasonably high resulting temperature gradient across the core.

The value of flux density to be chosen also depends upon the service conditions of the transformer. As a distribution transformer operates for all day efficiency, the flux density is kept as low as possible to keep down iron losses.

The usual values of flux density B_m for transformers using hot rolled silicon steel are:

Distribution transformer – 1.1 to 1.35 Wb/m^2

Power transformer – 1.25 to 1.45 Wb/m^2

For transformers using cold rolled grain oriented silicon steel laminations,

For transformers upto 132kV – 1.55 Wb/m^2

For 275 kV transformer – 1.6 Wb/m^2

For 400kV and generator transformer – 1.7 Wb/m^2

b) Design of Cooling tubes: If the temperature rise as calculated with plain tank exceeds the specified limits, it can be brought down by provision of tubes. The provision of tubes increase the dissipating area but the increase in dissipation of heat is not proportional to area of tube. An addition of 35 percent should be made to tube area in order to take into account this improvement in dissipation of losses by convection.

Let the dissipating surface of tank be S_t.

It will dissipate $(6 + 6.5)\, S_t = 12.5\, S_t$ $W/^0C$,

& let the area of tubes = $x\, S_t$

Loss dissipated by the tubes by convection = $1.35 \times 6.5 \times S_t = 8.8\, xS_t$ $W/^0C$

So, **total loss dissipated by tank and tubes** = $\mathbf{12.5\, S_t + 8.8\, xS_t = S_t\,(12.5 + 8.8\, x)}$ **$W/^0C$**

Total area of tank wall and tubes = $S_t + x\, S_t = S_t\,(1 + x)$

Thus, **loss dissipated** = $\mathbf{(12.5 + 8.8\, x) / (1 + x)}$ **$W/m^2\text{-}^0C$**

Temperature rise with tubes, $\theta = (P_i + P_c) / S_t\,(12.5 + 8.8\, x)$ Total area of tubes = $\mathbf{1/8.8\, [(P_i + P_c)/\theta - 12.5\, S_t]}$

or, $x = 1/8.8\, [(P_i + P_c) / (S_t\, \theta) - 12.5]$

Total area of tubes = $\mathbf{1/8.8\, [(P_i + P_c) / \theta - 12.5\, S_t]}$

Let l_t = length of each tube

& d_t = depth of each tube

So, area of each tube = $\pi\, d_t\, l_t$

Thus, **Number of tubes, $n_t = (1/ 8.8\, \pi\, d_t\, l_t)\, [(P_i + P_c) / \theta - 12.5\, S_t]$**

The area of the tubes can be found out by using the above equations. The diameter of tubes, normally, used in 50mm and they are spaced at 75mm. Elliptical tubes with pressed radiators are used as they give a greater dissipating surface for smaller volume of oil.

Q. 4: Derive the output equation for a synchronous machine. Discuss the factors which govern the choice of magnetic and electric loading. Explain the procedure to estimate the bore diameter and core length.

Sol: Output equation of synchronous machine: The output equation of an electrical machine can be expressed in terms of its main dimensions, specific magnetic and electrical loadings and speed, the equation describing this relationship is as output equation.

AC Machine:

Consider an 'm' phase machine having one circuit per phase. kVA rating of the machine is,

kVA, Q = no, of phases x output voltage per phase x current per phase x 10^{-3}

$Q = m\, E_{ph}\, I_{ph} \times 10^{-3}$

We have,

Induced emf per phase, $E_{ph} = 4.44\, f\, \Phi\, T_{ph}\, K_w$

So, kVA, $Q = m \times 4.44\, f\, \Phi\, T_{ph}\, K_w \times I_{ph} \times 10^{-3}$

But, $f = p\, n_s /2$

So, kVA, $Q = m \times 4.44\, (p\, n_s /2)\, \Phi\, T_{ph}\, K_w \times I_{ph} \times 10^{-3}$

or, kVA, $Q = 1.11\, K_w\, (p\, \Phi)\, (2\, m\, T_{ph}\, I_{ph}) \times n_s \times 10^{-3}$

As considered, there is only one circuit per phase, so $I_s = I_{ph}$

So, total number of armature conductors, Z = no. of phases x (2 x no. of turns per phase)

or, $Z = m \times (2\, T_{ph}) = 2\, m\, T_{ph}$

& total electric loading = $I_s\, Z = 2\, m\, T_{ph}\, I_s$

Hence,

kVA, $Q = 1.11\, K_w\, (p\, \Phi)\, (I_s\, Z) \times n_s \times 10^{-3}$

or, kVA, Q = 1.11 K_w (total magnetic loading) (total electric loading) (syn.

Speed) x 10^{-3}

But, $p\, \Phi = \pi\, D\, L\, B_{av}$, $I_s\, Z = \pi\, D\, ac$

Thus,

kVA, $Q = 1.11\, K_w\, (\pi\, D\, L\, B_{av})\, (\pi\, D\, ac) \times n_s \times 10^{-3}$

or, kVA, $Q = (1.11\, \pi^2 K_w\, B_{av}\, ac \times 10^{-3})\, D^2\, L\, n_s$

or, kVA, $Q = (11\, K_w\, B_{av}\, ac \times 10^{-3})\, D^2\, L\, n_s$

or kVA, $Q = C_0\, D^2\, L\, n_s$

&

$$Q = C_o . D^2.L.n$$

$$\text{output coefficient, } C_o = 1.11\pi^2 x\ B_{av}\ x\ ac\ x10^3$$

This equation is known as output equation of the ac machines.

Choice of specific magnetic loading: Some of the factors that influence the choice of average gap density. These factors along with some additional factors which are specific to choice of average flux density for synchronous machines are:

1. Iron loss: A high value of flux density in air gap leads to a high value of flux density in the stator teeth and core, resulting in high value of iron losses with decease in efficiency and increase in temperature rise. So, a lower value of flux density should be used in the machines

2. Voltage: In case the machines are design with high voltages, the space occupied for insulation becomes greater and smaller space is left for slot teeth. So, a lower value of flux density should be used to avoid the excessive flux density in core and teeth.

3. Transient short circuit current: A high value of flux density results in decrease in the leakage reactance of the machine with an increase in initial value of armature under short-circuit conditions. So, a low value of flux density should be used to limit the electromagnetic forces under short circuit conditions.

4. Stability: The maximum power which a cylindrical rotor can produce is $P_{max} = E\ V\ /X$, where E is the excitation voltage, V is the terminal voltage and X is the synchronous reactance. So, the maximum power is inversely proportional to syn. reactance. If the high value of gap density is used, then the flux per pole is large and smaller number of turns are required for armature winding & thus value of syn. reactance is reduced. So, steady state stability improves.

5. Parallel operation: All synchronous machines are connected in parallel in general with other synchronous machines. The satisfactory parallel operation of synchronous generators is dependent upon the **synchronizing power**. Higher this power, higher is the capability of the machine to be in synchronism. The synchronizing power is inversely proportional to syn. reactance and thus high value of flux density gives the higher value of synchronizing power and operates in parallel.

Choice of specific electric loading: Some of the factors that influence the choice of average gap density. These factors along with some additional factors which are specific to choice of average flux density for synchronous machines are:

1. Copper loss & temperature rise: A high value of ac leads to a high value of copper losses with decease in efficiency and increase in temperature rise. The value of ac also depends upon the cooling techniques employed. So, a lower value of ac should be used in the machines that effectively dissipate the heat

2. Voltage: A higher value of ac can be used for low voltage machines since the space required for insulation is small.

3. Synchronous reactance: The value of ac affects the syn. reactance and armature reaction in the machine. A high value of ac leads to high value of leakage reactance and armature reaction and thus a high of syn. reactance. So, the machine has poor voltage regulation, low current under short circuit conditions and a low value of steady state stability leads to instability.

4. Stray load loss: The stray load loss increase steeply with an increase in ac.

Main dimensions: Stator bore diameter D and core length L are called as main dimensions of the machine. The selection of diameter D depends upon

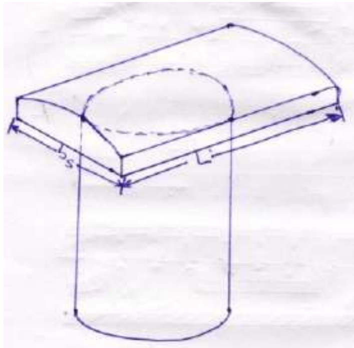
I) types of poles used.

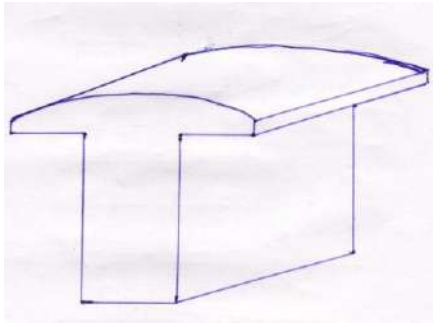
ii) the permissible peripheral speed

There are two types of poles used for salient pole machines, as shown:

i) Round poles.

ii) Rectangular poles.





Round Poles **Rectangular Poles**

I) **Round poles**: When round poles are used the ratio pole arc to pole pitch b_s / τ is between 0.6 to 0.7. Under these conditions it is possible to use round poles with square pole shoes.

So, for round poles,

Length of pole shoe, L = width of pole shoe, b_s

& **ratio, $L / \tau = 0.6$ to 0.7**

ii) **Rectangular poles**: When rectangular poles are used the ratio pole arc to pole pitch b_s / τ is between 1 to 5.

So, for rectangular poles,

ratio, $L / \tau = 0.6$ to 0.7

So, from the above equations, the diameter of circular poles is more than that of rectangular poles. The deciding factor for the diameter is the peripheral speed. The motor should ne designed to withstand the centrifugal forces produced under runaway speeds.

The values of peripheral speeds for different types of pole attachments are:

Bolted on pole construction = 50m/sec.

Dovetailed and T-head construction = 80m/sec.

UNIT-III

Q. 5: Explain the points to be accounted for the design of main winding, auxiliary winding and capacitor in a split phase induction motor.

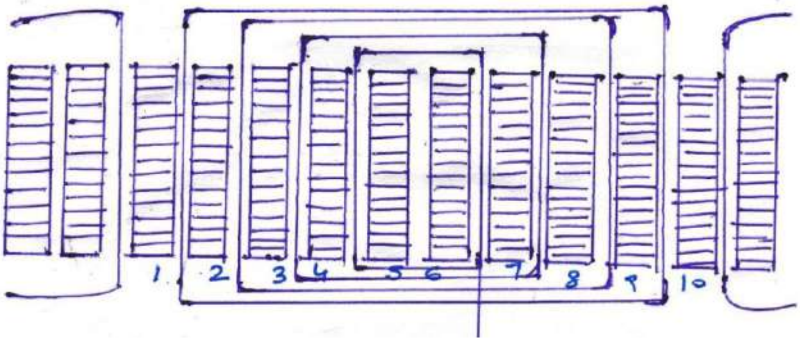
Sol:

Design of Main (running winding): The stator windings of a single-phase induction motors are concentric type. There are usually 3 or more coils per pole each having same or different number of turns.

The arrangement of winding is governed largely by the necessity of minimizing harmonic fluxes which may otherwise give rise to noise and uneven accelerating torque. Such harmonics produce non-sinusoidal shape of mmf wave. Mmf wave harmonics can be reduced by utilizing 70 percent of the total slots for the running winding as this arrangement gives minimum low order harmonics. The remaining slots (30 percent) are used for accommodating the starting windings.

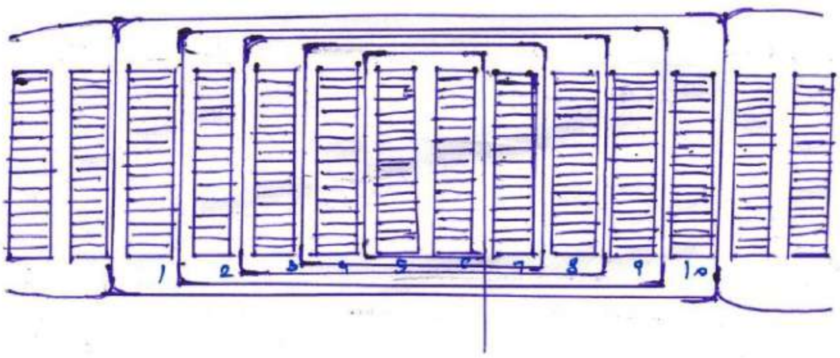
In a small single-phase induction motor may be desirable to reduce the harmonics still further by grading the winding i.e. by having different number of conductors in each slot thereby giving an mmf wave which becomes nearly sine wave.

Let the winding arrangement for an induction motor as shown in arrangement with 9 stator slots per pole. There are 4 coils per pole:



Coil (1-9)	-	it spans 8 slots
Coil (2-8)	-	it spans 6 slots
Coil (3-7)	-	it spans 4 slots
Coil (4-6)	-	it spans 2 slots

The coils can be re-arranged as shown in fig. below with again 4 coils per pole,.



Coil (1-10)	-	it spans 9 slots
Coil (2-9)	-	it spans 7 slots
Coil (3-8)	-	it spans 5 slots
Coil (4-7)	-	it spans 3 slots

With this arrangement the number of turns are lying of one side of the pole and other coil side on the other side of pole.

a) Number of turns of Running Winding: The number of turns in the stator running winding can be calculated as follows:

Stator Induced voltage, $E = 4.44\ f\ \Phi_m\ T_m\ K_{wm}$

where, T_m = no, of turns in running winding

K_{wm} = winding factor for running winding

So, number of turns on running winding T_m,

$$\mathbf{T_m = E / 4.44\ f\ \Phi_m\ K_{wm}}$$

& $\mathbf{\Phi_m = Bav \times (\pi DL / p)}$

The value of stator induced voltage E is equal to 85 percent of supply voltage V. The winding factor for the running winding can be assumed between 0.75 to 0.85.

Number of turns in series per pole for the main winding,

$T_{pm} = T_m / P$

a) **Running winding conductors:** Current carried by each running winding conductors,

$$I = h.p. \times 746 / (V \eta \cos Ø)$$

Area of running winding conductor, $a_m = I_m / \delta_m$

where, δ_m is the current density for running winding conductors in A/mm^2.

Design of Starting or Auxiliary winding: For a split-phase induction motors, after the satisfactory design of the main winding, the next step is to design a suitable starting or auxiliary winding. In order that the starting winding can produce a revolving field, a flux set up by the auxiliary winding must be out of phase with the flux set up by the main winding. The number of turns on the main winding satisfy the requirements of the core and the size of conductor requirement for the load. This means that the reactance of the main winding is high and its resistance is low. The starting winding must have parameters just the reverse of those of main winding flux, i.e. the starting winding must have high starting resistance and low reactance, as the flux produced should be out of phase with that produced by the main winding.

It is essential to design the best possible starting winding for the main winding and rotor. For any given main winding, there are almost an unlimited number of starting winding arrangements.

With the resistance split phase motors the required resistance is usually obtained by using a small section of wire i.e. about 25% of that of main winding. The current density at starting may be as high as $100A/mm^2$. The phase angle between starting winding current and line voltage should be about 0.4 of that for the main winding.

Design of Capacitor: Improvements in capacitor design and construction are making the capacitor start split phase motor more effective than resistance split phase induction motor. This motor is a little more expensive but it gives higher starting torque and lower starting current.

The design of starting winding for a capacitor start motor generally presents the design of the combination of starting winding and capacitor to work in conjunction with the main winding. Cost of the capacitor depends upon its microfarad rating and the voltage. Actual voltage across the capacitor may be in excess of the line voltage depending upon the design.

Starting Torque for capacitor start induction motor:

$$T_s = (1/2\pi) \times (p\, C_r\, K\, r_{rm}' / f)\, I_{sm}\, I_{sa} \sin(\theta_m - \theta_a)$$

or,

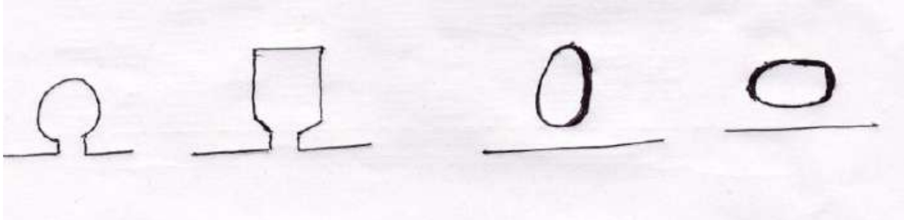
$$T_s = (1/2\pi) \times (p\, C_r\, K\, r_{rm}' / f)\, \frac{V^2\, R_a\, X_{lm} - R_m\, (X_{lm} - X_a)}{(R_m^2 + X_m^2)\,(R_a^2 + X_{la} - X_c)^2}$$

where, X_c = reactance of the capacitor.

Q. 6: a): Discuss the selection of "rotor-slot shape" in the design of cage induction machines.

b): Find the current in the bars and end rings of a cage rotor of 6-pole, 3-phase induction motor having 72 stator slots with 15 conductors in each slot. Stator current per phase is 20A and rotor slots are 55. Determine the size of cage bars and end rings. Current density $5A/mm^2$ for rotor bars and $7A/mm^2$ for end rings.

Sol: Shape and size of rotor slots: The rotor slots for squirrel cage rotor may either be closed or semi-closed type slots, as shown:



Types of rotor slots

Closed slots are preferred for small size machines because the reluctance of the air gap is not large owing to absence of slot openings. This gives a reduced value of magnetizing current. As the surface of rotor is smooth, the operation of the machine is quieter. The biggest advantage is that the leakage reactance with closed slots is large and thus, the current at stating is limited. This is very useful in the case of machines which are started with direct-on-line starters. Bu the disadvantage is that the increased value of reactance results in reduction in the overload capacity.

The rectangular shaped bars and slots are generally preferred to circular bars and slots as the increases the rotor resistance at starting and improves the starting torque. Deep slots give an increased leakage reactance and a high value of flux density at the root of the teeth.

b): Given that: no. of poles, P = 6

no.of stator slots, Ss = 72

no.of rotor slots, Sr = 55

So, no. of stator slots per pole per phase, q = 72 / (6 x3) = 4

Assume the winding factor with 4 slots per pole per phase is **Kw = 0.956**

Given that, stator current per phase, Is = 20A

Stator current equivalent to rotor current, Ir "= Is x cosØ

where, cosØ = stator power factor ≈0.83 (assume)

So,

Stator current equivalent to rotor current, Ir" = 16.6A

Stator turns per phase, Tph = no. of conductors per slot x no. of slots / 6

or, **Tph = 75 x 15 / 6 = 180**

Thus, current in rotor bar,

Ib = (2 x m x Kws x Tph / Sr) x Ir" = (2 x 3 x 0.956 x 180 / 55) x 16.6

or, **I_b = 311.62A**

& Current in end ring, **I_e = 909.26A**

$I_e = S_r \times I_b / (\pi p) = (55 \times 311.62) / (\pi \times 6) = 909.26A$

I_e = 909.26A

Given that, current density of rotor bars, $\delta_b = 5A/mm^2$

& current density of rotor end ring, $\delta_e = 7A/mm^2$

So, area of rotor bars, $a_b = I_b / \delta_b = 311.62 / 5 = 298.6mm^2$

$a_b = I_b / \delta_b = 298.6mm^2$

& area of end rings, $a_e = I_e / \delta_e = 909.26 / 7 = 129.9\ mm^2$

$a_e = I_e / \delta_e = 129.9\ mm^2$

UNIT-IV

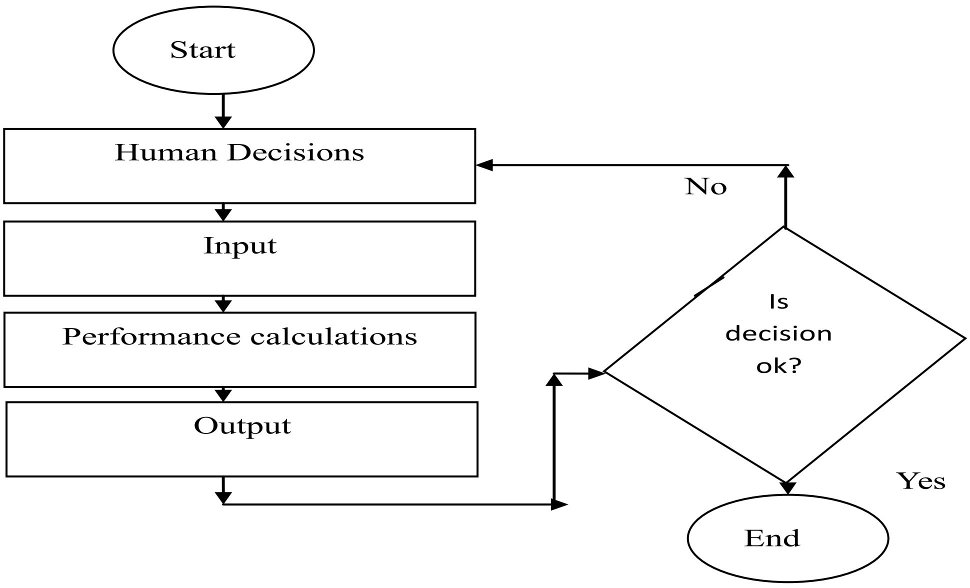
Q. 7: Give a list of optimization techniques. With the help of flow chart discuss the applications of any optimization technique for the design of transformers.

Sol: Optimization techniques: The concept of optimization in electrical machine design was introduced by Godwin in 1959 and a program was developed for design of squirrel cage induction motors. In 1959, Heroz introduces the concept of two commonly acceptable approaches to machine design, namely:

i) Analysis method and ii) Synthesis method.

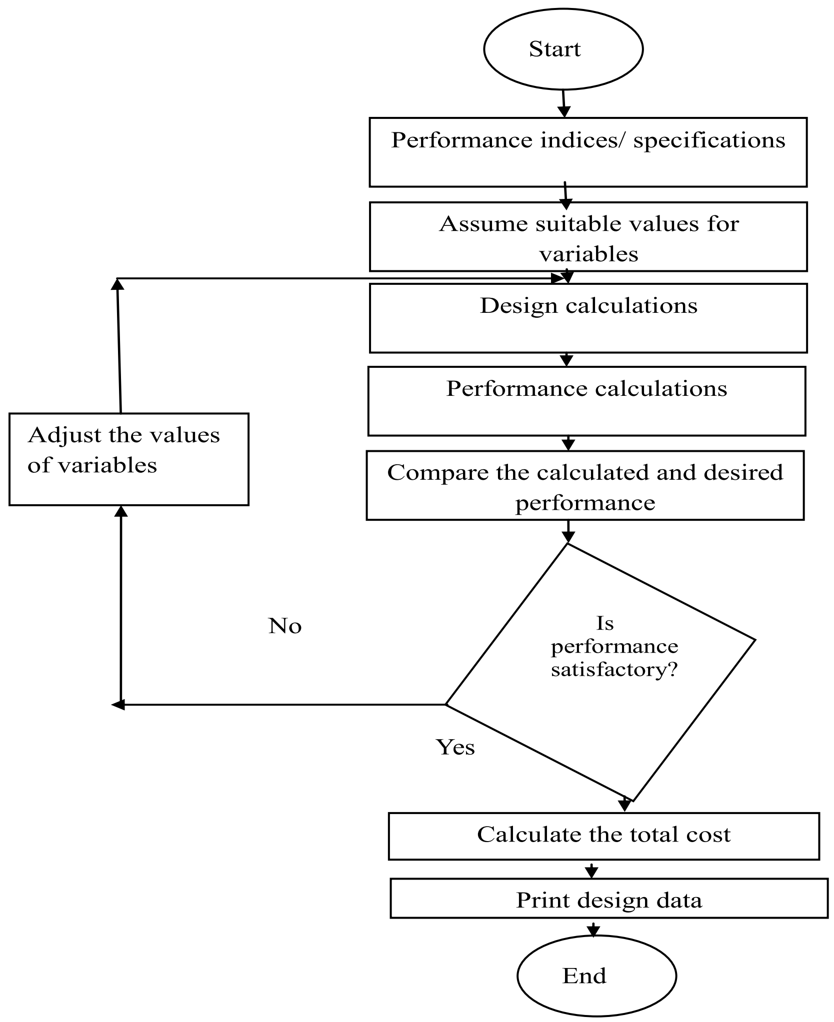
I) Analysis Method: The analysis method of design is depicted as in fig. In this method, the choice of dimensions, materials and type of construction are made by the designer and these are presented as input data to the computer. The performance was calculated by the computer and is returned to the designer for examination. The designer examines the performance and makes choice of input, if necessary and performance is recalculated. This procedure is repeated till the performance requirements are satisfied.

The use of term ”analysis method” means the use of computer for the purpose of analysis leaving all exercises of judgement to the designer.



ii) Synthesis Method: The synthesis method is as depicted in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

The greatest advantage of synthesis method is as the saving in time in lapsed time and in engineering man hours on account of the decision left to the computer itself.



iii) Hybrid Method: This method incorporates both the analysis as well as synthesis methods in the program. Since the synthesis methods involve greater cost, the major part of the program is based upon the analysis with a limited portion of the program being based upon synthesis.

Computer aided design for designing transformers: The transformer is a static device which transfers the electrical energy from one or more primary windings to one or more secondary windings using the law of electro-magnetic induction using the magnetic circuit. Class of transformers (power or distribution), type of construction (core or shell type), kVA ratings, voltage level, type of connections, percentage of impedances and tappings, temperature rise are the basic requirements of customer's specifications.

To achieve the better performance, the whole design procedure is divided into several parts as follows:-

i) Core design

ii) Window dimension design

iii) Yoke design

iv) Overall design

v) Low voltage winding design

vi) High voltage winding design

vii) Resistance calculation.

viii) Leakage reactance calculation.

ix) Loss calculation.

x) Efficiency calculation.

xi) No-load current calculation.

1. Core design: Core design is dealt with the type of core (core or shell) of the transformer. The value of 'K' is constant depending upon the type of transformer (power or distribution). The allowable flux density in the core lies between 1.0 to 1.35Wb /m^2 for distribution transformer and between 1.25 to 1.45 Wb/m^2 for power transformers. The core section of the core type transformer can be

a. Square.

b. Cruciform or 2-stepped

c. 3-stepped

d. 4-stepped

2. Window dimensions: Flux density in the window section of the transformer is same as that of the core of the transformer. For large power transformers upto 50kVA self cooled, current density, δ, usually lies between 1.1 to 2.3 A/mm^2, for large power transformers self-oil cooled or air blast type, δ = 2.2 to 3.2 A/mm^2 and for large power transformers with forced circulation of oil or water cooled transformers, δ = 5.4 to 6.3 A/mm^2.

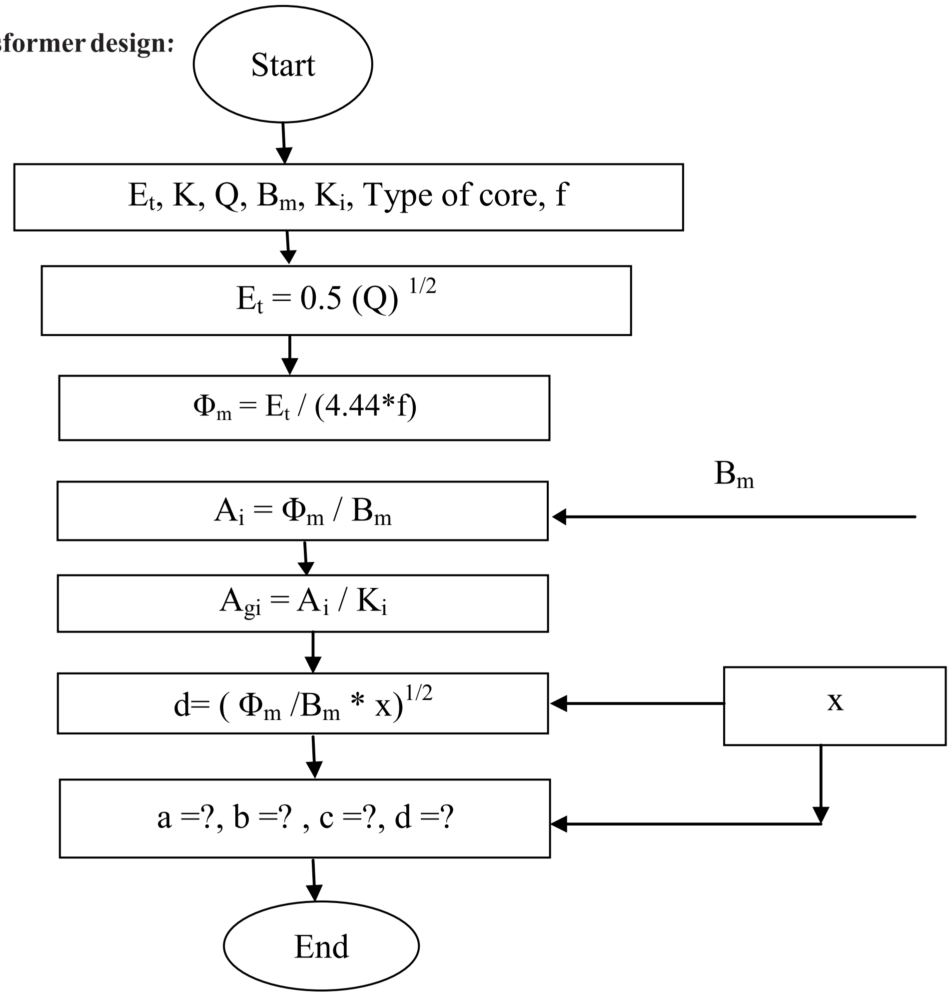
3. Yoke design: Area of the yoke is taken as 15 to 25 percent larger than that of the core of the transformer. The section of the yoke is either rectangle or square. For rectangular yoke, the yoke highest side of the laminated core (width of the largest stamping) is taken as depth core.

4. Low voltage winding design: For the selection of low voltage winding, either helical, cylindrical or cross over winding arrangements are preferred. Dimensions of the conductor of the low voltage winding is taken based on the area of the conductor.

5. High voltage winding design: Design of high voltage winding is similar to the low voltage winding design. Higher percentage of tapping increase the flexibility of transformer. Thus, helical or cross over winding arrangements are preferred in this case and dimensions of the conductor of the low voltage winding is taken based on the area of the conductor.

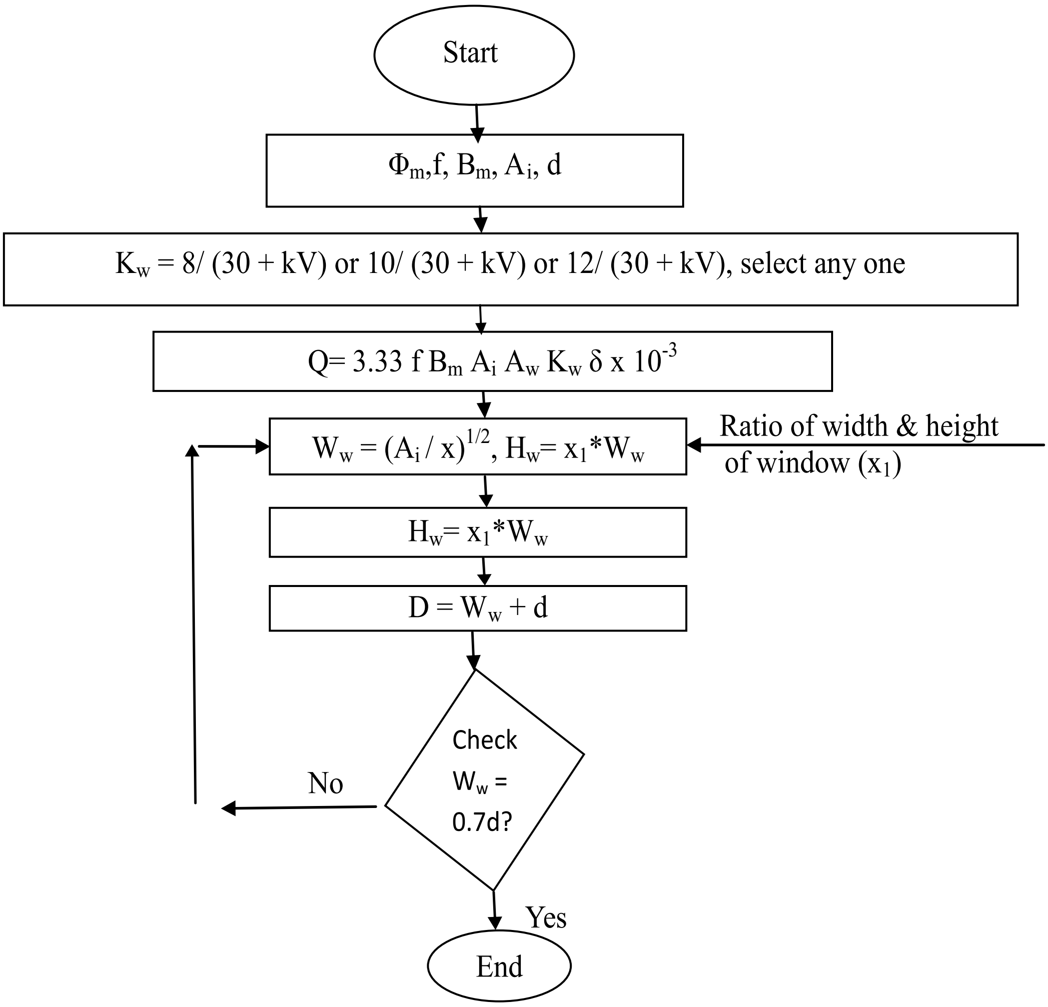
Flow charts for Transformer design:

Core design:

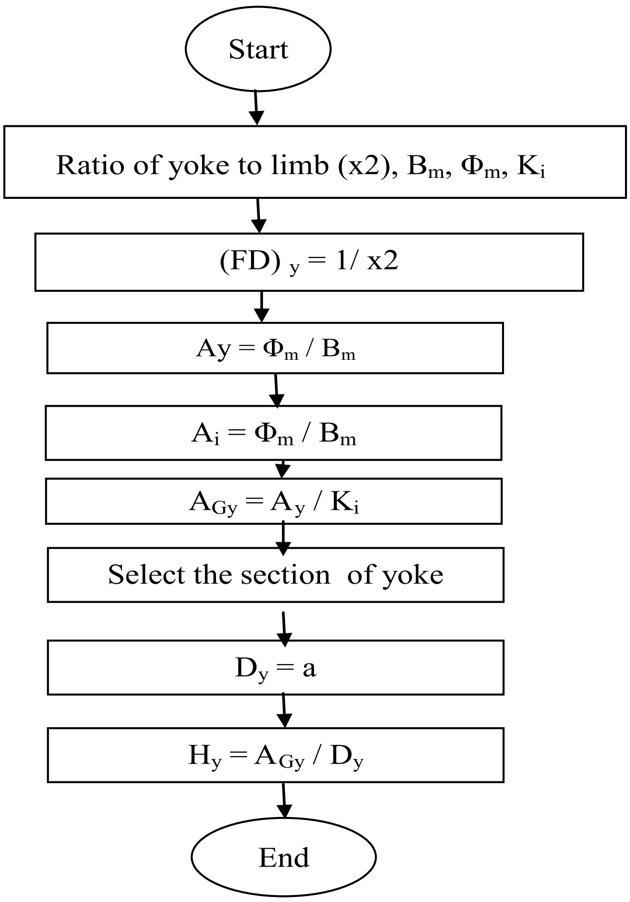


"x" indicates corresponding values of selected type of core.

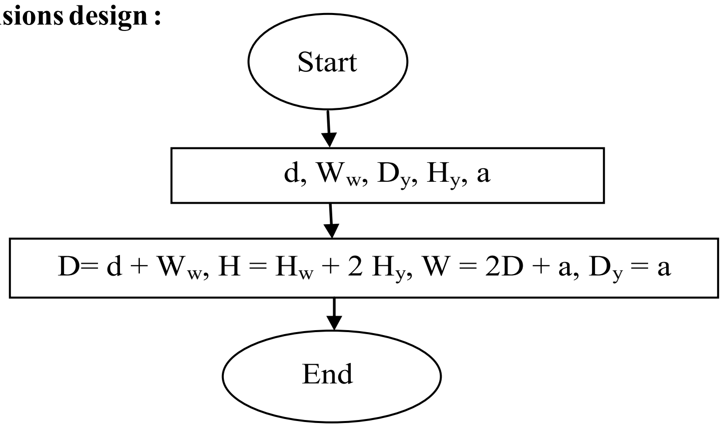
Window dimensions Design:



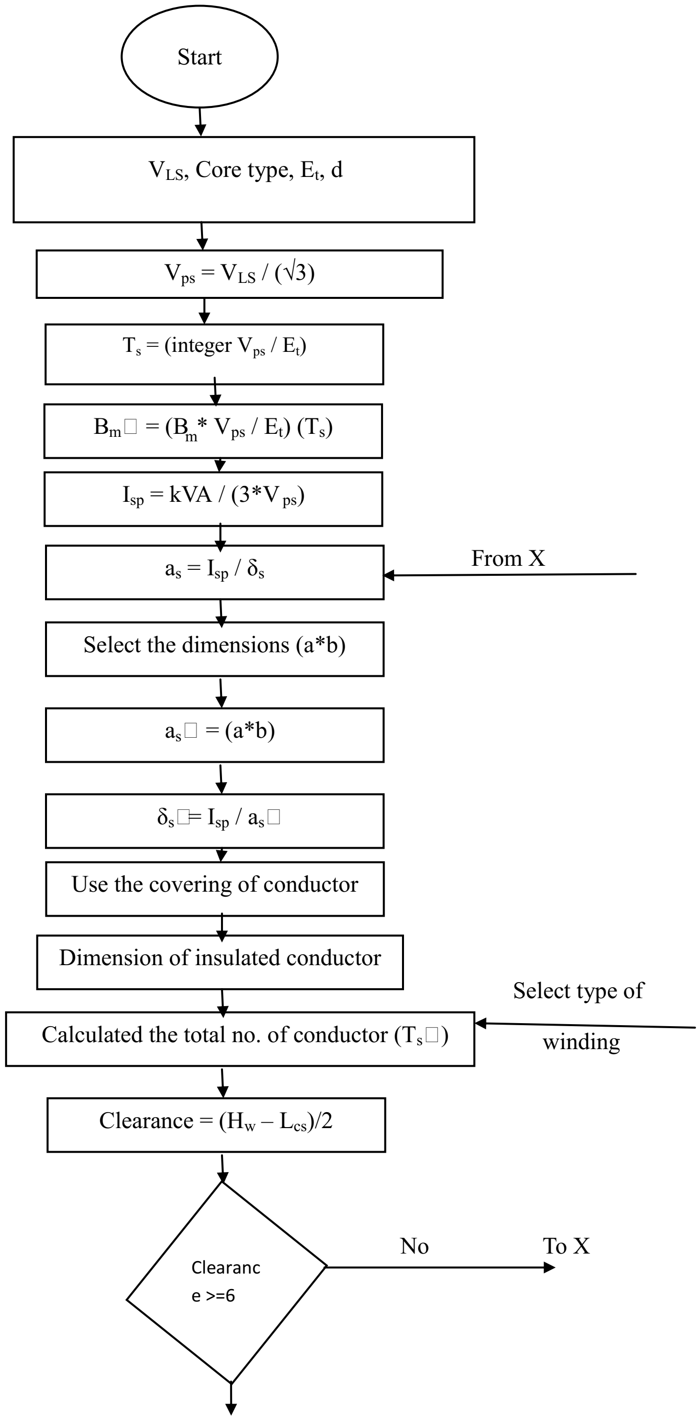
Yoke design:

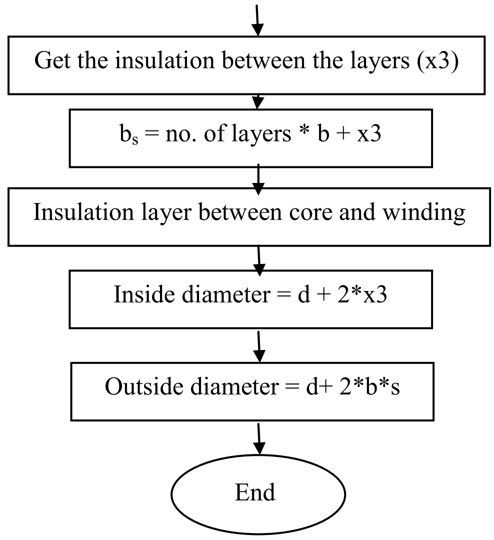


Overall dimensions design :

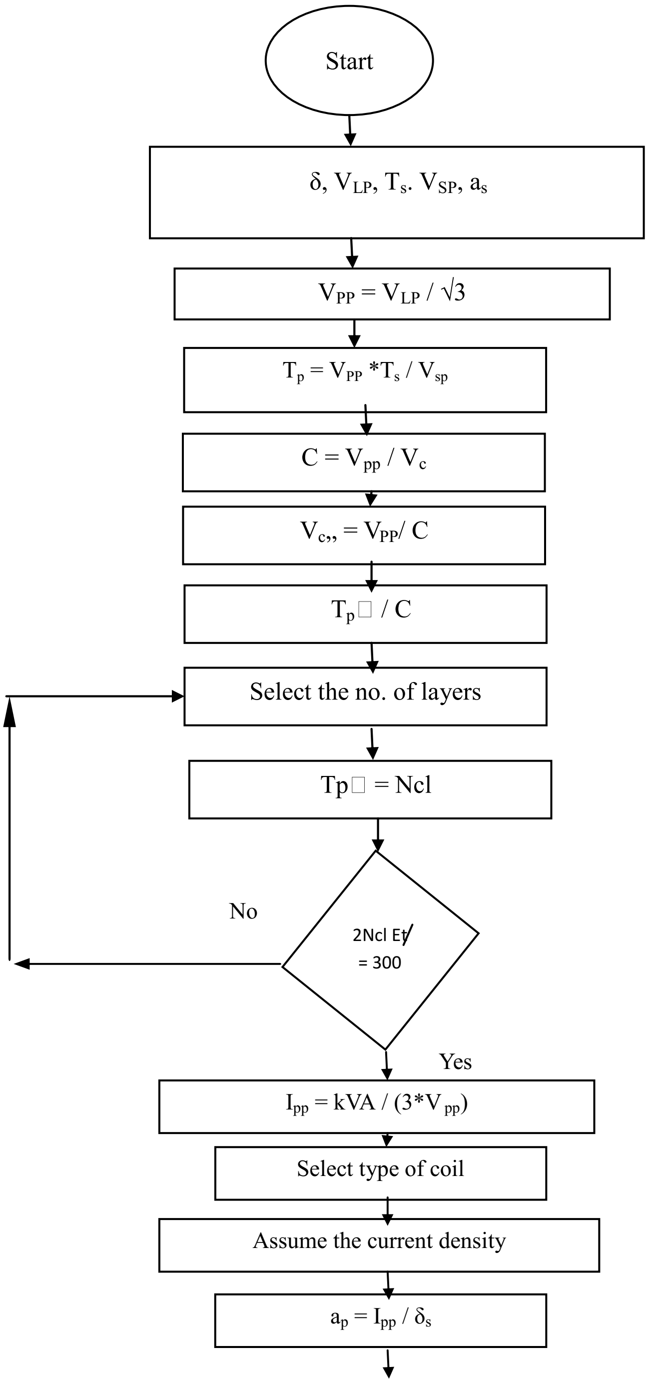


L.V. Winding design:





H.V. Winding design:



$d = (4/\pi * a_p)^{1/2}$

↓

Select conductor size

↓

d', d''

↓

$a_s' = \pi/4 * d'^2$

↓

$\delta_p = I_{pp} / a_s'$

↓

H_{cp} = Turn/ layer * d”

↓

Use space between adjacent coils

↓

L_{cp} = no. of coil * axial depth of each coil + depth of spacers

↓

Clearance = $(H_w - L_{cp})/ 2$

↓

Use insulation between the layers

↓

b_p = no. of layers * d” + (No. of layers-1) * insulation

↓

T = 5 + 0.9 kV

↓

Inside diameter = Outside of LV + 2 * thickness of insulation

↓

Outside diameter = Inside diameter HV + 2*T

↓

End

Resistance calculations:

Start

↓

D_{HV1}, D_{HVO}, T_p, L_{mtp}, a_p, D_{LV1}, D_{LVO}, T_s, a_s

↓

$Dph = (D_{HV1} + D_{HVO})/2$

↓

$R_p = T_p . \rho . L_{mtp} / a_p$

↓

$D_{SM} = (D_{LV1} + D_{LVO}) / 2$

↓

$L_{mts} = \pi * D_{SM} * 10^{-3}$

↓

$R_s = T_p . \rho . L_{mts} / a_p$

↓

$R_{pf} = Rp + (Tp/Ts) Rs$

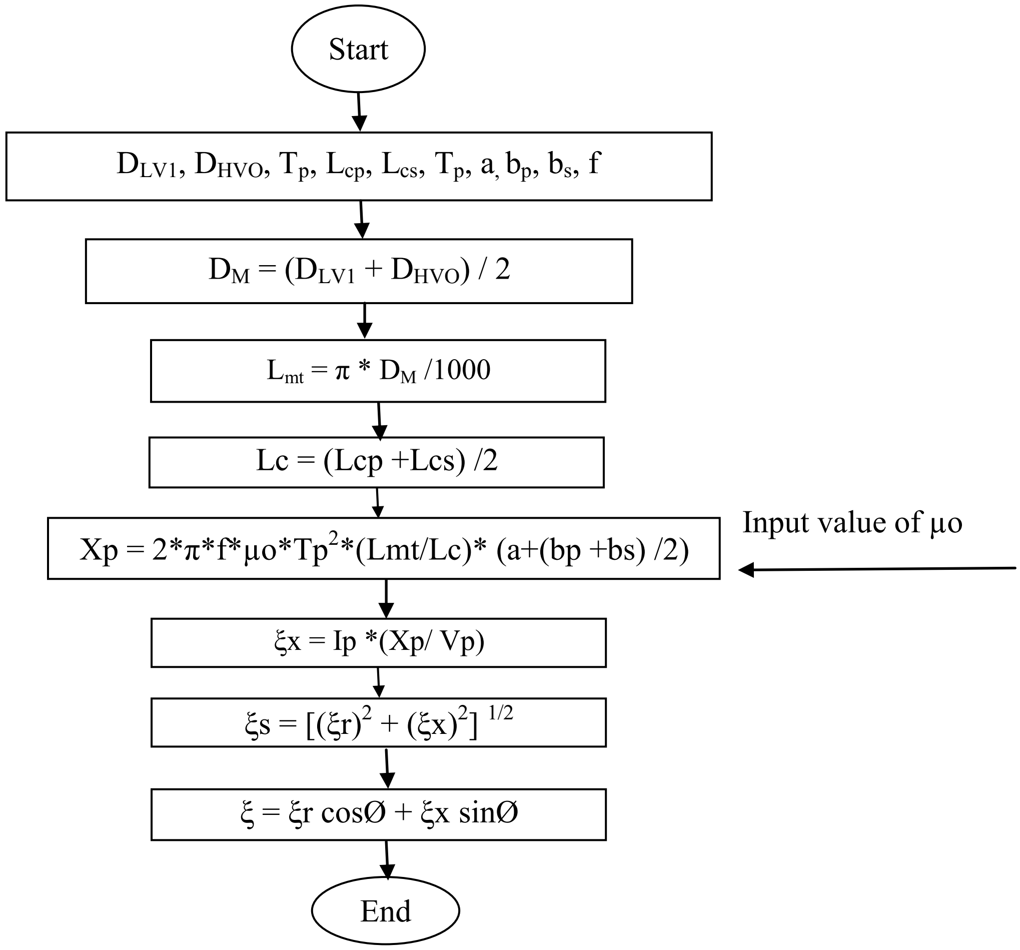
↓

$\varepsilon_r = Ip * Rp / Vp$

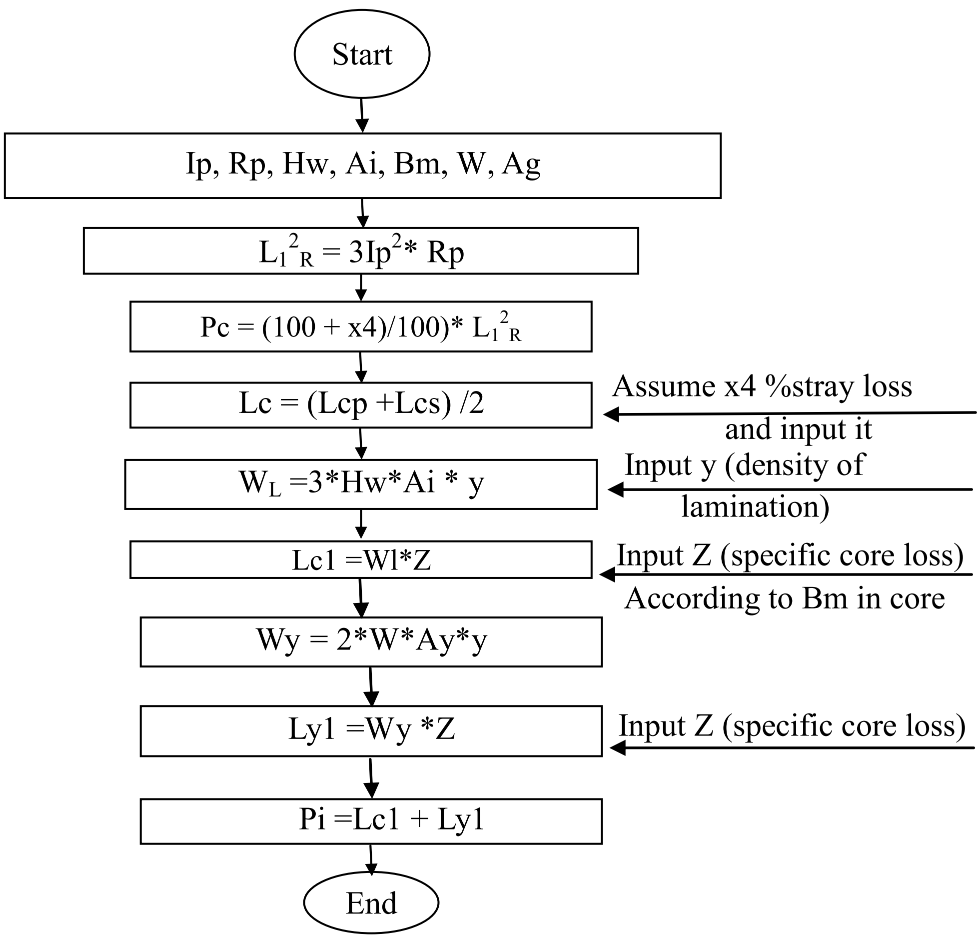
↓

End

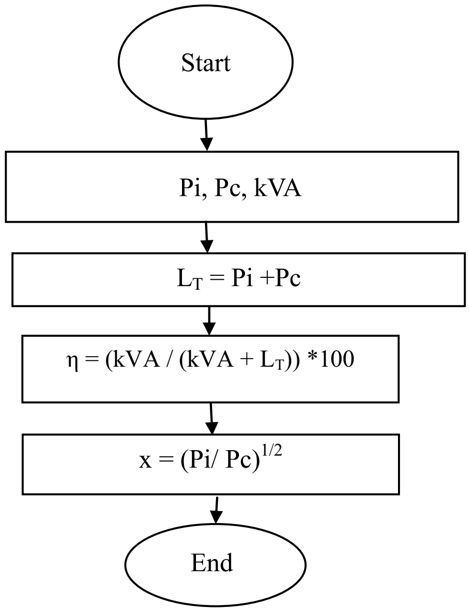
Leakage reactance calculations:



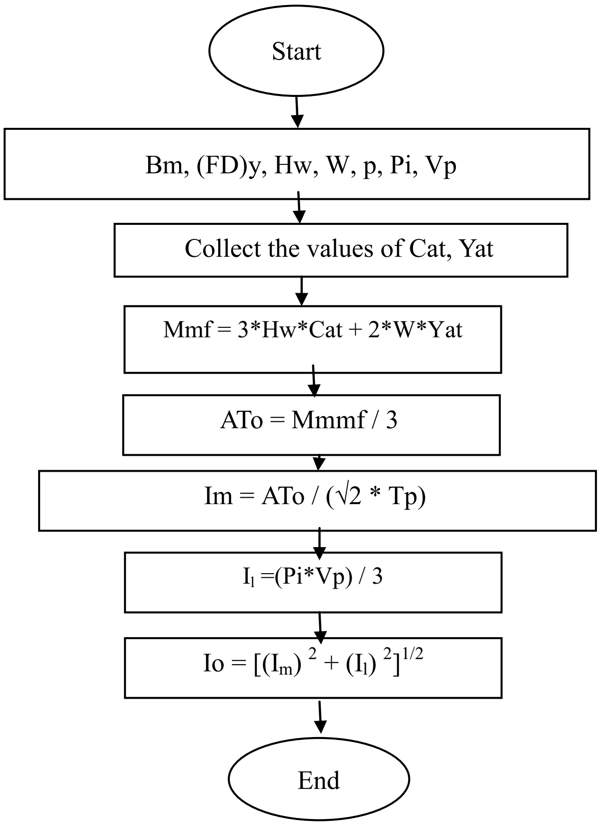
Loss calculations:



Efficiency calculations:



No load Current calculations:



Cat = value of ampere conductors per turn turns to the value of flux density in core

Yat = value of ampere conductors per turn turns to the value of flux density in yoke

Q. 8: Discuss the role of computers in the design of electrical machines. What are the major difficulties of 'Computer aided design'? Discuss 'Synthesis' design approach.

Sol: Role of computer and major difficulties in Electrical machine design: The design of electrical machine (including transformers) consist essential solutions of many complex and diverse engineering problems and these problems are interrelated to each other. Thus, the electrical machine design is a mathematical indeterminate problem with many solutions, as number of unknowns is greater than the no. of equations. But the machine design can be achieved by correct decisions based upon the judgement and intuition and very clear understanding of the project. In today's world, the prime endeavour of an electrical machine lies in designing the machine suited to the work place, such as:

a) Good performance that fits into the technical specifications.

b) Permissible cost of the machine.

c) Satisfactory life of the machine in comparison to the cost.

d) Higher operating range and suitable for multi-tasking.

e) Easy maintenance and simple in construction.

The manual design procedure of a machine is very time consuming and tedious work, needs more man power and less accuracy. Further, during the manual design, lot of approximations are required to be considered which gives inaccurate results. Thus, we can use a so-called computer language to solve the above mentioned problems and thus this approach is called as **Computer aided electrical machine design**.

The process of design of a single electrical machine may be divided into three major design problems:

i) Electromagnetic design

ii) Mechanical design

iii) Thermal design

The above problems can be solved separately and the results thus obtained, are combined later on. Additionally, each of these problems may be subdivided into simple but loosely related elements. Each element is considered as a separate problem and thus the solution can be found out as an acceptable solution.

The other aspect of the present day design of electrical machines is designing a set of machines, all of which form a part of a single system. The different machines connected in such a system react upon each other, sometimes considerably and on occasions drastically. So, the machines require to operate on a system cannot be designed for isolation and thus the designs of all such machines have to be completed concurrently since the design of one machine is closely related to the design of other machines. Thus for these problems, optimization techniques are required for.

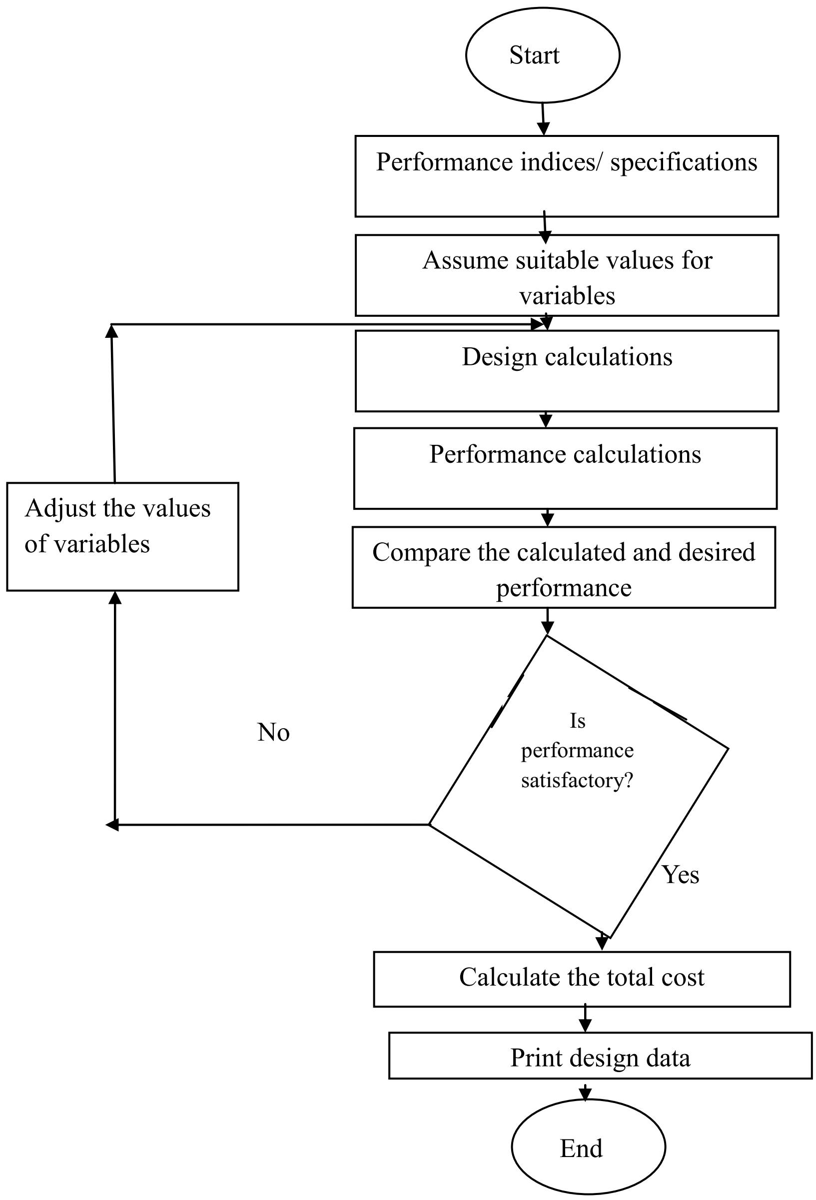
It is often desired to design a series of machines having different ratings to fit into a given frame size. In this case, the machines over a range of ratings use the same diameter (D) but different core lengths (L) to achieve the required outputs. In this case, the finished designs of machines must be produced in groups, where all the designs within a group are interdependent.

It takes many iterations to arrive at an optimal solution. The iterations require changes of values of variable for cost as well as performance constraints are achieved.

Thus, at last, it can be stated that the design of electrical machines is an iterative process wherein the assumed data may have to be varied many a times to arrive a desired design. Thus, due to above factors and circumstances, wide spread use of digital computers for design of electrical machines.

Synthesis design approach: The synthesis method is as depicted in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

The greatest advantage of synthesis method is as the saving in time in lapsed time and in engineering man hours on account of the decision left to the computer itself.



The synthesis method suffers with a number of serious disadvantages such as:-

1) This method involves too much logic since the logical decisions are left to the computer to take. Now, these logical decisions have to be incorporated in the program and before, incorporation, the team of design engineers are to agree upon them.

2) The logical decisions to arrive at a optimum design are too many and then, there are too many people with too many ways to suggest to produce the optimum design and thus, it becomes really hard to formulate a logic for obtaining an optimum design.

3) The formulation of a synthesis program taking into account of factors listed would make it too complex. So, cost of computer program becomes high and thus use of a large computer and also large running time involves huge expenditure.

4) The synthesis program formulated at a high cost cannot be used for ever, as due to changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions etc., the program has to be changed and up dated keeping. Thus synthesis method requires additional efforts and cost in order for the above.

Electrical Machine Design

SOLVED QUESTION PAPER-9

UNIT-INote: Attempt *Five* questions in all, selecting at least one question from each unit. All questions carry equal marks. Assume any missing data if required.

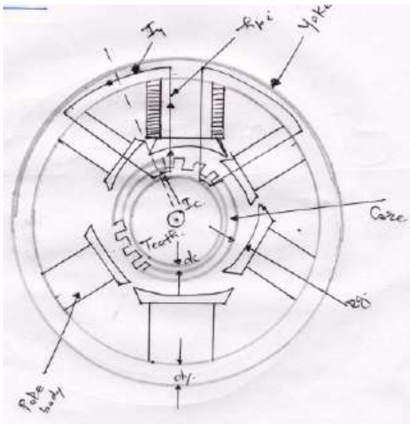
UNIT-I

Q. 1: Discuss major design aspects of the following in relation to d.c. machines.

Brushes, Commutator, Yoke, Interpole

Sol:

Design of Yoke: The dimensions of yoke are determined by the value of Φ_y carried by the yokes. The leakage coefficient for yoke is a little higher than that for the poles. From the fig., as shown, it is clear that the yoke carries half of the total flux.



Flux in the yoke, Φ_y = leakage coefficient x ½ useful flux per pole = ½ C_1 Φ

The flux density in the cast steel yokes is normally equal to 1.2Wb/m^2 while in laminated yokes, it is about 1.5Wb/m^2.

So, **Area of yoke, $A_y = \Phi_y / B_y$** & **depth of yoke, $d_y = \Phi_y / (B_y \times L_{yi})$**

where, B_y = flux density in the yoke and L_{yi} = net axial length of yoke.

In the case of cast steel yokes, the net axial length of yoke is equal to the actual axial length of yoke.

For machines with laminated yokes the net axial length of yoke is equal to iron length of armature.

Design of Interpoles: The interpoles are made from laminated steel or from low carbon steel. Laminated interpoles are used in machines with severe commutation problems. In small machines, it is usual to use solid low carbon steel poles. Interpoles may be parallel sided or tapered. In large machines, tapered interpoles are used in order to ensure that there is no saturation at the root of the pole at overloads.

Interpoles are smaller poles placed in between the main poles. The polarity of interpole must be that of the main pole just ahead for a generator and just behind for a motor. The winding of an interpole must produce an mmf which is sufficient to neutralize the cross magnetizing armature mmf at the interpolar axis and enough more to produce the flux density required to generated rotational voltage in the coil undergoing commutation. Thus, the appropriate field mmf required at the geometric neutral axis to generate the neutralizing rotational voltage is produced by **interpoles or commutating poles**. Since both the armature reaction and reactance voltage are proportional to armature current, the interpole winding should be so connected in series with the armature for production of neutralizing effect at all conditions of load. In order to preserve linearity, the interpoles should be so designed that they work at low saturation levels. So, with the use of interpoles, a sparkles commutation is secured over a wide range.

Width of interpole shoe: If a straight line commutation is desired, the width of interpole shoe should not be less than the width of commutation zone, w_c. An allowance of 1.5 to 2 times the length of air gap under the interpole can be considered at interpole tips.

So, **width of interpole shoe, $W_{ip} = w_c - (1.5 \text{ to } 2)\, l_{gi}$**

where, l_{gi} = length of air gap under interpole shoe.

The length of air gap under the interpole l_{gi} must not be so small as to produce large pulsations of the interpole flux caused by the armature slots. It must not be too large so that the main pole flux will penetrate the interpole air gap. So, **$l_{gi} = (1 \text{ to } 2)\, l_i . W_{ip} \leq ((1-\psi)/2)\,\tau$**

The interpole width must also be so chosen that the leakage flux is not excessive. To avoid excessive leakage flux, the width of interpole must be as given,

$$W_{ip} \leq ((1-\psi)/2)\,\tau$$

& the width of interpole shoe is so chosen that the width of interpole shoe is related to armature slot pitch as, **$W_{ip} \geq 1.5\, Y_s$**.

Length of interpole: The interpoles are made of cast steel or punched from sheet steel with no special pole shoe; that is the length and width of pole body are equal to the length and width of pole shoe.

The length of interpole is so chosen from the point of economy, for the shorter the interpole, the shorter will be the length of mean turn of interpole winding and the smaller copper weight, losses and leakage flux. The length must be so chosen that the flux density in the interpole will be below the saturation point of the material. This is required for the proper compensation of reactance voltage at all loads.

For machines designed for large fluctuating loads or for variable speed motors, which employ completely laminated core, the length of interpole is take equal to the main pole.

Flux density under interpole shoe: As the mean emf generated in the coils undergoing commutation, by their rotation in reversing field under the interpole, must be equal to reactance voltage, so that the total emf is zero under short circuit conditions.

Let, B_{ci} = flux density under the interpole

& L_{ip} = length of interpole

So, the rotational emf produced in a coil under interpole,

$E_{pi} = 2 \text{ x } T_c$ x voltage generated in each conductor $= 2\,.T_c .\, B_g .\, L_{ip} .\, V_a$

This voltage must balance the reactance voltage E_{rac} in each turn, **$E_{rac} = 4\, T_c\, \lambda\, L\, I_z\, Z_s / T_c$**

So, **$4\, T_c\, \lambda\, L\, I_z\, Z_s / T_c = 2\,.T_c .\, B_g .\, L_{ip} .\, V_a\;\; B_{gi} = 2\, I_z\, Z_s\, (L / L_{ip}) \text{ x } (1 / V_a\, T_c) \text{ x } \lambda$**Hence, the flux density under interpole shoe, $B_{gi} = 2\, I_z\, Z_s\, (L / L_{ip}) \text{ x } (1 / V_a\, T_c) \text{ x } \lambda$

$$B_{gi} = 2\, I_z\, Z_s\, (L / L_{ip}) \text{ x } (1 / V_a\, T_c) \text{ x } \lambda$$

Further reactance voltage in coil of T_c turns, $E_{rac} = 2\, T_c\, ac\, V_a\, \lambda\, L$

So, $2\,.T_c .\, B_{gi} .\, L_{ip} .\, V_a = 2\, T_c\, ac\, V_a\, \lambda\, L$

or, **$B_{gi} = ac\, \lambda\, (L / L_{ip})$**

Design of interpole winding: The length of air gap under the interpole is relatively large and the iron parts of interpole magnetic circuit are worked much below the saturation region.

Let, l_{gi} = length of air gap under interpole

K_{gi} = interpole gap contraction factor

AT_a = armature mmf per pole $= I_z\, Z / 2\, p$

Mmf required to establish a flux density, $B_{gi} = 800{,}000\, B_{gi}\, K_{gi}\, l_{gi}$

Mmf required to overcome the armature reaction = $I_z Z / 2p$

Total mmf required for interpole, $AT_i = 800{,}000\, B_{gi} K_{gi} l_{gi} + I_z Z / 2p$.

The interpole winding is connected in series with the armature and the total armature current flows through the interpole winding. A single-layer coil wound strip on edge may be used for the winding. For large machines, a conductor having two or more strips in parallel may be used. So, the number of interpole turns, T_i is given by,

Number of interpole turns, $T_i = AT_i / I_a$

The current density in the interpole winding should lie between 2.5 to 4 A/mm^2, the higher value is used where ventilation is good and the insulation is thin.

Design of Commutator and Brushes:

Number of Segments: The number of segments is equal to the number of coils or segments C = ½ u S.

The minimum no. of segments, which gives a voltage of 15V between the segments at no-load, is

Minimum no. of segments = E x p /15

Commutator diameter: The diameter of commutator generally lies between 0.6 to 0.8 of armature diameter. It varies from 62% of armature diameter for 350/700V machines, 68% for 200/250V machines and 75% for 100/125V machines.

The peripheral voltage gradient around the commutator should be limited to about 3V/mm in order to avoid ionization of the skin in the air at the commutator surface. Thus for a 600V machine the minimum peripheral distance between adjacent brush arms should be 200mm. The diameter must be chosen with regard to the peripheral speed and the thickness of commutator segment.

Peripheral speed: The commutator peripheral speed is kept below 15m/sec. Higher peripheral speeds upto 30m/sec. are used but should be avoided.

Commutator segment pitch: The thickness of the commutator at the commutator surface should not less than 3mm. So, the pitch of segment is given by,

Pitch of segment, $\beta_c = \pi D_c / C$, should not be less than 4mm.

Length of Commutator: The length of commutator depends upon the space required by the brushes and the surface required for dissipate the heat generated by the commutator losses.

Dimensions of brushes: The thickness of brushes has a profound influence on the commutation conditions. So, the thickness of brush is so selected that it covers 2 to 3 commutator segments.

Current carried by each brush spindle is $2 I_a / p$, so total brush contact area per spindle,

Total brush contact area per spindle, $\mathbf{A_b = 2 I_a / p \times \delta_b}$

where, δ_b is the current density in the brushes from 0.1 to 0.2 A/mm^2 for various types of materials of brushes.

Let, n_b = number of brushes per spindle, and w_b and t_b are width and thickness of each brush respectively. Contact area of each brush, $a_b = w_b \times t_b$

So, total contact area of brushes in the spindle,

$A_b = n_b \times a_b = n_b \times w_b \times t_b$ $\mathbf{w_b = Ab / n_b \times t_b = 2 I_a / p\, \delta_b\, n_b \times t_b}$ So, width of each brush,

$$w_b = Ab / n_b \times t_b = 2 I_a / p\, \delta_b\, n_b \times t_b \;\; m^3/sec$$

The number n_b is so selected that each brush carries current less than 70A.

Length of commutator, $L_c = n_b (w_b + c_b) + C_1 + C_2$

where, c_b = clearance between the brushes and depends upon the construction of brush holder, it is usually 5mm. C_1 is the clearance allowed for staggering of brushes, varies from 10mm for small machines to 30mm for large machines. C_2 is the clearance for allowing the end play and is usually between 10 to 25mm.

Q. 2: Discuss any four types of Duty cycle for rotating electrical machines. Explain the various methods of estimate

the motor rating for variable load drives.

Sol: Types of duties and ratings: The following are the types of duty as per IS standards:

I) S_1: Continuous duty.

ii) S_2: Short time duty.

iii) S_3: Intermittent periodic duty.

iv) S_4: Intermittent periodic duty with starting.

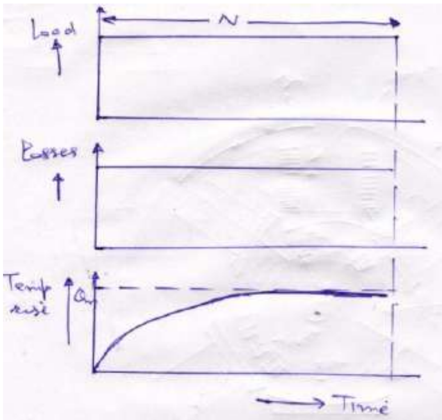
v) S_5: Intermittent periodic duty with starting and braking.

vi) S_6: Continuous duty with intermittent periodic loading.

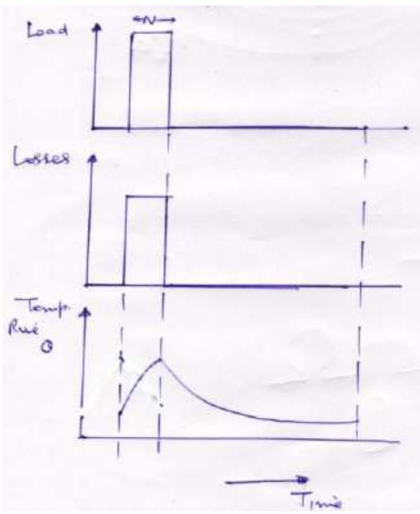
vii) S_7: Continuous duty with starting and braking.

viii) S_8: Continuous duty with periodic speed changes.

S_1: Continuous duty: On this duty, the duration of load is for a sufficiently long time such that all parts of the motor attain thermal equilibrium, i.e. the motor attains the such that all parts of the motor attain thermal equilibrium, i.e. the motor attains the maximum final steady temperature rise. Examples of such drives are fans, pumps and other equipment which operate several hours and even days at a time. The simplified load-diagram for this duty is as shown in figure as horizontal line

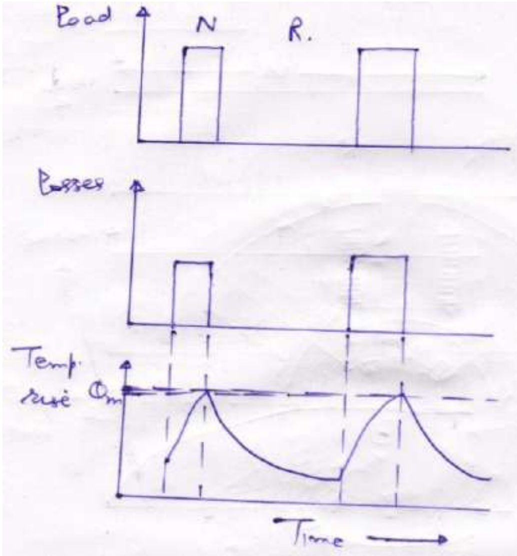


ii) S2: Short time duty: The motor operates at a constant load for some specified time which is then followed by a period of rest. The period for load is so short that the machine cannot reach its thermal equilibrium. Railway turntable, navigation lock gates are some examples of this drive. The simplified load diagram for short time duty is as shown in fig.



The short time rating of a motor may be defined as its output at which it may be operated for a certain specified time without exceeding the maximum permissible value of temperature rise. Standard short time ratings are: 10, 30, 60 and 90 minutes.

iii) S3: Intermittent periodic duty: On intermittent duty, the periods of constant load and rest with machined-energized alternate. The load periods are too short to allow the motor to reach its final steady state value, while periods of rest are also too small to allow the motor to cool down to the ambient temperature. This type of duty cycle is encountered in cranes, lifts and metal cutting machine tool drives. The simplified load diagram of this duty cycle is as shown in fig. .



For evaluation of intensity of heating due to intermittent period loads, the factor called duty factor is used. The **Duty factor** or **Load factor** or **Cyclic duration factor** is defined as the ration of the heating (working) period to the period of whole cycle.

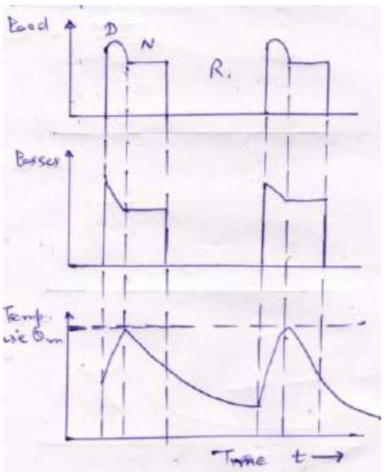
So, **duty cycle,** $\varepsilon = t_h / (t_h + t_c)$

where, t_h = heating period and t_c = period of rest.

The intermittent rating of a motor applies to an operating condition during which short time load periods alternate with periods of rest or no load without the motor reaching the thermal equilibrium and without temperature rise above the maximum permissible value. The duty factor, for this operation is:

Duty cycle, $\varepsilon = N / (N + R)$

I) **S_4: Intermittent periodic duty with starting**: This type of duty consists of a sequence of identical duty cycles each consisting of a period of starting, a period of operation at constant load and a rest period. The operating and rest periods are too short to obtain thermal equilibrium during one duty as shown in fig.



In this duty, the stopping of the motor is obtained either by deceleration after disconnection of the electric supply or by means of braking such as mechanical brakes which does not cause additional heating of the motor. The duty factor, for this operation is:

Duty cycle, $\varepsilon = (D + N) / (D + N + R)$

Methods used for determination of motor rating for variable load drives: The four commonly methods used for the determination of proper rating of the motors for variable load drives:

a) Method of average losses.

b) Equivalent current method

c) Equivalent torque method, &

d) Equivalent power method

a) Method of average losses: This method consists of finding average losses Q_{av} in the motor when it operates according to the given load diagram. These losses are then compared with Q_{nom}, the losses corresponding to the continuous duty of the machine when operated at its normal rating. The method of average losses presupposes that when $Q_{av} = Q_{nom}$, the motor will operate without temperature rise going above the maximum permissible for a particular class of insulation.

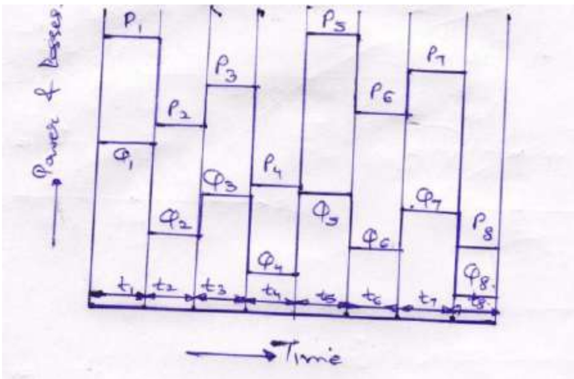
$$\theta_{per} = Q_{nom} / (S\lambda)$$

& $$\theta_m = Qav / (S\lambda)$$

$$\boldsymbol{\theta_m = \theta_{per} = Qav / (S\lambda) = Q_{nom} / (S\lambda)}$$

Fig. shows a simplified load diagram for a certain load drive. The loss diagram (Q versus time) of the electric motor is as shown. The rating of the motor can be found from method of successive approximations. The losses of the motor are calculated for each portion of load diagram. The average losses are given by

$$Q_{av} = (Q_1 t_1 + Q_2 t_2 + \ldots + Q_n t_n) / (t_1 + t_2 + \ldots + t_n)$$



The average losses Q_{av}, can be found from the above equation, are compared with the losses of selected motor at rated efficiency. In case, the two losses are equal or differ by a small amount, the motor is selected. However, in case, the two losses differ considerably, another motor is selected and the calculations are repeated till a motor having same amount of losses as the average losses.

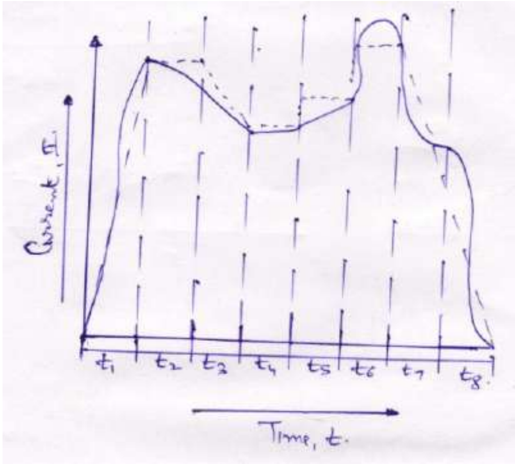
This method of average losses does not take into account of the maximum temperature rise under variable load conditions. However, this method is accurate and reliable for determining the average temperature rise of the motor during one work cycle. The disadvantage of this method is that it is tedious to work with and also many a times the efficiency curve is not readily available.

a) Equivalent current method: The equivalent current method is based upon the assumption that the actual variable current may be replaced by an equivalent current I_{eq}, which produces the same losses in the motor as the actual current. This method also assumes that the constant losses are independent of load.

$$I_{eq} = \sqrt{(I_1^2 t_1 + I_2^2 t_2 + \ldots + I_n^2 t_n) / (t_1 + t_2 + \ldots + t_n)}$$

•The heating and cooling conditions in self ventilated machines depends upon the speed. At low speeds the cooling conditions are poorer than at normal speeds.

•The equivalent current as found from the above equation should be compared with the rated current of the motor selected and the conditions $I_{eq} \leq I_{nom}$, should be met. The equivalent current may not be easy to calculate especially in cases where the current load diagram is irregular as shown in fig.



The above method allows the equivalent current values to be calculated with accuracy sufficient for practical purposes.

c) Equivalent Torque & Equivalent Power method: It often becomes necessary to use torque or power load diagram for the selection of motor capacity. The equivalent torque or power is found in the same manner as that of equivalent current method.

The torque is directly proportional to current and thus, the equivalent torque is:

$$\mathbf{T_{eq} = \sqrt{} (T_1^2 t_1 + T_2^2 t_{2+ \ldots\ldots\ldots\ldots} + T_n^2 t_n) / (t_1 + t_2 + \ldots\ldots\ldots\ldots + t_n)}$$

The above relationship also assumes that the electromagnetic torque and the torque available at the shaft are approximately equal. The equation of equivalent power follows directly as power is proportional to torque. At constant speed or where the changes in speed are small, the equivalent power is given as under:

$$\mathbf{P_{eq} = \sqrt{} (P_1^2 t_1 + P_2^2 t_{2+ \ldots\ldots\ldots\ldots} + P_n^2 t_n) / (t_1 + t_2 + \ldots\ldots\ldots\ldots + t_n)}$$

The equivalent current method is the most accurate method out of all three methods. This method may be used to determine the motor capacity for all uses except where it is necessary to take into account the changes. The equivalent torque method cannot be used for selection of motor rating for cases in which the field flux does not remains constant like d.c. series motors.

The disadvantage of equivalent power method is that it cannot be used for motors whose speed varies considerably under load, especially when starting and braking conditions are applied.

UNIT-II

Q. 3: Determine the dimensions of the core and yoke of 100kVA, 50Hz, single-phase core type transformer. A square core is used with distance between the adjacent limbs equal to 1.6 times the width of laminations. Assume voltage per turn of 14V, maximum flux density 1.1Wb/m^2, window space factor 0.32 and current density 3amp/mm^2. Take stacking factor = 0.9. Flux density in the yoke to be 80% of the flux density in the core.

Sol: Given that, kVA = 100kVA

f = 50Hz, 1-phase core type transformer

Distance between adjacent limbs, D = 1.6 x width of lamination, a

$B_m = 1.1\ Wb/m^2$

$\delta = 3amp/mm^2 = 3 \times 10^{-6}\ A/m^2$

Stacking factor, $K_s = 0.9$

Window space factor, $A_w = 0.32$

As given, voltage per turn, $E_t = 14$ V

or, $Et = 4.44\, f\,\Phi_m = 4.44\, f\, B_m A_i = 14$

So,

Area of iron core, $A_i = 0.0573m^2$

So, gross iron area, $A_{gi} = A_i / K_s = 0.0573 / 0.9 = 0.0637m^2$

As given, square core is used, so,

Gross iron area, $A_{gi} = 0.5d^2 = 0.673$

Thus, **Diameter of circumscribing circle, d = 0.37m**

Width of largest stamping, **a = 0.71d = 0.71 x 0.37 = 0.26m**

As given, **D = 1.6 x a = 1.6 x 0.26 = 0.417m**

Width of window, $W_w = D - d = 0.417 - 0.37 = 0.047m$

For a single phase core type transformer, output equation is,

$$Q = 2.22\, f\, B_m A_i A_w K_w \delta \times 10^{-3}$$

So,

Area of window, $A_w = 0.0149m^2$

Thus, **height of window, $h_w = A_w / W_w = 0.0149 / 0.047 = 0.317m$**

For square core of yoke of core,

Depth of yoke $D_y = a = 0.26m$

As given, flux density in yoke, $B_y = 0.8\, B_m$

So, **area of yoke, $A_y = (1/0.8)\, A_i = (1/0.8) \times 0.0573 = 0.0716m^2$**

Thus, **height of yoke, $h_y = A_y / D_y = 0.275m$**.

Overall dimensions:

Overall height of frame, $H = h_w + 2\, h_y = 0.317 + 2 \times 0.275 = 0.868m$

Overall width of frame, $W = D + a = 0.417 + 0.26 = 0.677m$

Q. 4: Compare Turbo-alternators with Hydro generators. Give the procedure to design the rotor of hydro generator. Discuss the role of damper windings in synchronous machines.

Sol: Comparison of Turbo-generators with Hydro-generators:-

Sr. No.	Hydro-Generators	Turbo-Generators
1.	The synchronous generators driven by the water turbines are known as hydro-generators or water wheel generators	The synchronous generators driven by the steam turbines are known as turbo-generators or turbo-alternators
2.	These machines are rated upto 750MW and are driven at speeds ranging from 100 to 1000 rpm.	These machines are rated upto 1000MW and run at a speed of 1500rpm or 3000rpm
3.	The no. of poles constructed on the rotor are large and are constructed on salient-pole construction.	The no. of poles on the rotor are limited to 2 and are of cylindrical rotor construction.
4.	These machines have the peripheral speed of 140m/sec. Thus these machines have larger diameter of the armature and smaller core length.	The diameter of these machine is limited to 1.2m giving a peripheral speed of 175m/sec.

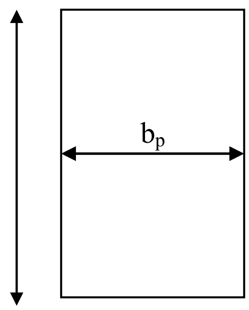
5.	Hydro-generators are either vertical or horizontal shaft type driven by pelton wheels, whereas the Francis or Kaplan water turbines always have vertical shafts.	Turbo-generators are always horizontal shaft type driven by steam turbines.
6.	Hydro-generators are more stable and have more transient stability under the mechanical consideration like centrifugal forces, deflection of shaft an critical speed.	Turbo-generators are less stable under the mechanical consideration like centrifugal forces, deflection of shaft an critical speed.
7.	Hydro-generators are easily cooled due to larger diameter and lees core length.	Turbo-generators have complex engineering problems of cooling due to limited diameter.

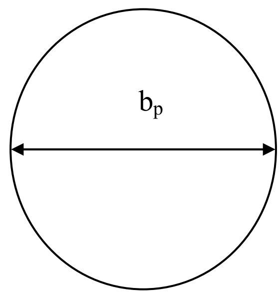
Design of Rotor of Hydro-generators:

Flux in pole body, Φ_p = leakage coefficient x useful flux per pole

or, $\mathbf{\Phi_p = C_1 \Phi}$

The value of leakage coefficient C_1 lies between 1.15 to 1.2.





So, area of cross-section of pole body, $A_p = \Phi_p / B_p$

The flux density in pole body B_p has a permissible value of 1.5 to 1.7 Wb/m^2.

For rectangular poles, area of pole body, A_p is.

$$\mathbf{A_p = 0.98 \times L_p \times b_p}$$

The axial length of poles, L_p may be taken equal to core length, L & the stacking factor is 0.98.

For circular poles, area of pole body, A_p is.

$$\mathbf{A_p = (\pi / 4) \times b_p^2}$$

Height of pole body: Since the dimensions of pole, yoke etc., are not completely known. Thus, only the estimation of the value of field mmf can be done.

No-load field mmf, $AT_{fo} = SCR \times At_a$

Armature mmf per pole, $AT_a = 2.7 \times I_{ph} \times T_{ph} K_{ph} / p$

Copper area of field winding = (full load field mmf) / (current density in the field winding)

So, **Copper area of field winding = AT_{fl} / δ_f**

The current density, δ_f can be taken between 3 to $4A/mm^2$.

Total space required for field winding = total copper area in field winding / space factor

The value of space factor for winding can be taken about 0.8 to 0.9 (0.4 for small round wires, 0.65 for large round wires and 0.75 for rectangular conductors).

So,

Height of winding, h_f = total space for field winding / depth of winding (d_f)

Take depth of winding (d_f) for the various pole pitches in the machines, as,

Pole Pitch, mm	Winding depth (d_f), mm
0.1	25
0.2	35
0.4	45
0.6	55
0.7	59

Furthermore, the height of field winding can also be estimated as:

Mmf per meter height of field winding = $10^4 \times \sqrt{(S_f d_f q_f)}$

where, S_f = copper space factor in field winding

d_f = depth of field winding, mm

q_f = loss per unit surface area, W/ m^2

So, **height of field winding, $h_f = AT_{fl}$ / Mmf per metre height**

Take height of flanges as 20mm

So, **height of pole body, $h_p = h_f + 0.02$ m.**

& **radial height of pole, $h_{pl} = h_p + h_1$ m.**

The ratio of radial length of pole to its pole pitch is normally between 0.3 to 1.5.

Role of damper windings: In synchronous generators, damper winding is provided to suppress the negative sequence field and to damp out the oscillations during hunting. For synchronous motors, the damper winding has different purpose: it is provided i) to start the motor and ii) to damp out the oscillations and to develop the damping power during hunting.

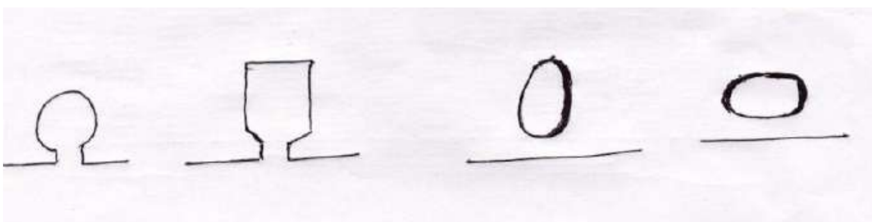
The damper windings are housed in the pole shoes. These damper windings consist of heavy copper rods, one in each slot or hole riveted at the ends of common bars one at each end so as to form short circuited grids or end bars. These short-circuiting end bars are carried right around the rotor so that they form two short-circuiting rings around the periphery. This coverts damper winding into a cage winding.

The damper windings are subjected to considerably high centrifugal forces as the peripheral speed of synchronous machine is very high. So, special attention must be paid to connecting bars in the rotor.

UNIT-III

Q. 5: Discuss the effects of shape of rotor slots in cage induction motor. Find the current in rotor bar and end rings of a cage rotor of a 6-pole, 3-phase induction motor having 72 stator slots with 15 conductors in each slot. Stator current per phase is 20amp and rotor slots are 55.

Sol: Shape and size of rotor slots: The rotor slots for squirrel cage rotor may either be closed or semi-closed type slots, as shown:



Types of rotor slots

Closed slots are preferred for small size machines because the reluctance of the air gap is not large owing to absence of slot openings. This gives a reduced value of magnetizing current. As the surface of rotor is smooth, the operation of the machine is quieter. The biggest advantage is that the leakage reactance with closed slots is large and thus, the current at stating is limited. This is very useful in the case of machines which are started with direct-on-line starters. Bu the disadvantage is that the increased value of reactance results in reduction in the overload capacity.

The rectangular shaped bars and slots are generally preferred to circular bars and slots as the increases the rotor resistance at starting and improves the starting torque. Deep slots give an increased leakage reactance and a high value of flux density at the root of the teeth.

Given that: no. of poles, $P = 6$

no. of stator slots, $S_s = 72$

no. of rotor slots, $S_r = 55$

So, no. of stator slots per pole per phase, $q = 72 / (6 x3) = 4$

Assume the winding factor with 4 slots per pole per phase is $\mathbf{K_w = 0.956}$

Given that, stator current per phase, $I_s = 20A$

Stator current equivalent to rotor current, $I_r' = Is \times \cos Ø$

where, $\cos Ø$ = stator power factor ≈0.83 (assume)

So,

Stator current equivalent to rotor current, $I_r' = 16.6A$

Stator turns per phase, T_{ph} = no. of conductors per slot x no. of slots / 6

or, $\mathbf{T_{ph} = 75 \times 15 / 6 = 180}$

Thus, current in rotor bar, $\mathbf{I_b = 311.62A}$

$I_b = (2 \times m \times K_{ws} \times T_{ph} / S_r) \times I_r' = (2 \times 3 \times 0.956 \times 180 / 55) \times 16.6$

or, $\mathbf{I_b = 311.62A}$

& Current in end ring, $\mathbf{I_e = 909.26A}$ $I_e = S_r \times I_b / (\pi$

$p) = (55 \times 311.62) / (\pi \times 6) = 909.26A$

$\mathbf{I_e = 909.26A}$

Assume, current density of rotor bars, $\delta_b = 5A/mm^2$

& current density of rotor end ring, $\delta_e = 7A/mm^2$

$\mathbf{a_b = I_b / \delta_b = 298.6mm^2}$ So, area of rotor bars, $a_b = I_b / \delta_b = 311.62 / 5 = 298.6mm^2$

$\mathbf{a_b = I_b / \delta_b = 298.6mm^2}$

$\mathbf{a_e = I_e / \delta_e = 129.9\ mm^2}$ & area of end rings, $a_e = I_e / \delta_e = 909.26 / 7 = 129.9\ mm^2$

$\mathbf{a_e = I_e / \delta_e = 129.9\ mm^2}$

Q. 6: Develop the output equation for a single-phase induction motor. Discuss the selection of electric and magnetic loading in this machine. Give and explain the selection of stator slots.

Sol: Output equation of 1-phase induction motor: The output equation of an electrical machine can be expressed in terms of its main dimensions, specific magnetic and electrical loadings and speed, the equation describing this relationship is as output equation.

<u>**AC Machine**</u>:

Consider a 1- phase machine having one circuit per phase, kVA rating of the machine is,

kVA, Q = output voltage per phase x current per phase x 10^{-3}

$Q = E_{ph} I_{ph} \times 10^{-3}$

We have,

Induced emf per phase, $E_{ph} = 4.44 f \Phi T_{ph} K_w$

So, kVA, $Q = 4.44 f \Phi T_{ph} K_w \times I_{ph} \times 10^{-3}$

But, $f = p n_s / 2$

So, kVA, $Q = 4.44 (p n_s /2) \Phi T_{ph} K_w \times I_{ph} \times 10^{-3}$

or, kVA, $Q = 1.11 K_w (p \Phi) (2 T_{ph} I_{ph}) \times n_s \times 10^{-3}$

As considered, there is only one circuit per phase, so $I_s = I_{ph}$

So, total number of armature conductors, Z = (2 x no. of turns per phase)

or, $Z = (2 T_{ph}) = 2 T_{ph}$

& total electric loading $= I_s Z = 2 T_{ph} I_s$

Hence,

kVA, $Q = 1.11 K_w (p \Phi) (I_s Z) \times n_s \times 10^{-3}$

or, kVA, $Q = 1.11 K_w$ (total magnetic loading) (total electric loading) (syn. Speed) x 10^{-3}

But, $p \Phi = \pi D L B_{av}$, $I_s Z = \pi D ac$

Thus,

kVA, $Q = 1.11 K_w (\pi D L B_{av}) (\pi D ac) \times n_s \times 10^{-3}$

or, kVA, $Q = (1.11 \pi^2 K_w B_{av} ac \times 10^{-3}) D^2 L n_s$

or, kVA, $Q = (11 K_w B_{av} ac \times 10^{-3}) D^2 L n_s$

or kVA, $Q = C_0 D^2 L n_s$

$Q = C_o . D^2 . L . n$

&

output coefficient, $C_o = 1.11\pi^2 \times B_{av} \times ac \times 10^3$

This equation is known as output equation of the ac machines.

If the machine rating is in horse power, we have:

$Q = h.p \times 0.746 / (\eta \cos Ø)$

& **$D^2.L = h.p \times 0.746 / (\eta \cos Ø \, C_0 \, n_s)$**

The range of full load efficiency and power factor is:

Efficiency: It ranges from 50 percent for a 75W to 70 percent for a 750W motor.

Power factor: It ranges from 0.55 for a 75W to 0.65 for a 750W motor.

Choice of Specific Loadings:

The usual values of average flux density in the air gap is:

$B_{av} = 0.35$ to 0.55 Wb/m^2

The usual values of specific electric loadings are:

$ac = 5000$ to 15000A/m

The values of product (C_0 η Cos Ø) can be read as under:

Watt/r.p.sec.	3.6	7.2	12	14	15	18
Product C_0 η cos Ø (m^3)	9.5	12	15.5	16.5	16.75	18

Selection of Stator slots: The various aspects of stator slots are to be considered for 1-phase induction motor designing, such as number of stator slots, size of stator slots, stator teeth, stator core etc.

1. **Number of stator slots**: A large number of slots reduced the leakage reactance. Thus, we can take more output from the motor frame and can have better overload capacity and better efficiency and better power factor. A large no. of stator slots also reduces the problems of harmonics and cogging.

But with large no. of slots, the space factor for slots becomes poorer, so, thus there is an upper limit for no. of slots, which in turn depends upon the size of the machine.

Thus, the number of stator slots per pole is usually between 9 to 12. For a 1-phase induction motor, the number of stator slots per poles should be real so that a regular winding is obtained.

2. **Size of Stator slots**: As the stator slots carries both running windings and starting winding conductors. The starting winding conductor has a small cross-sectional area and its effect on size of slot is small, whereas the running winding conductor with large no. of turns will determine the size of slot. **As in 1-phase induction motors, semi-closed slots are preferred, the insulation between core and coil is placed in the slots as slot lining. The slot liner is of 0.3 to 0.4mm thick**.

The ratio of insulated conductor area to the slot area should never exceed 0.5.

Let Z_s is the total no. of conductors per slot and d_1 mm is the diameter of insulated conductor.

Then, area required for insulated conductor $= Z_s \times (\pi/4)\, d_1^2$

So, **Minimum slot area required** $= (1/0.5) \times Z_s \times (\pi/4)\, d_1^2$

The average slot width,

$$W_{s(av)} = \pi (D + d_{ss}) / S_s - W_{ts}$$

where, d_{ss} = depth of stator slot, W_{ts} = width of stator teeth

S_s = number of stator slots

So, **Area of each slot** $= W_{s(av)} \times d_{ss}$

3. **Stator teeth**: The stator tooth density B_{ts} can generally be from 1.4 to 1.7 Wb/m^2. For general purpose machines, a flux density of 1.45Wb/m^2 and for high torque machines, it may go up to 1.8Wb/m^2.

Take stacking factor, $K_s = 0.95$

So, **Net iron length,** $L_i = 0.95\, L$

Flux density in the stator teeth, $B_{ts} = \Phi_m / ((S_s/p) \times L_i \times W_{ts})$

4. **Stator Core**: The flux density in the stator core should not exceed 1.5Wb/m^2. Generally it lies between 0.9 to 1.4Wb/m^2.

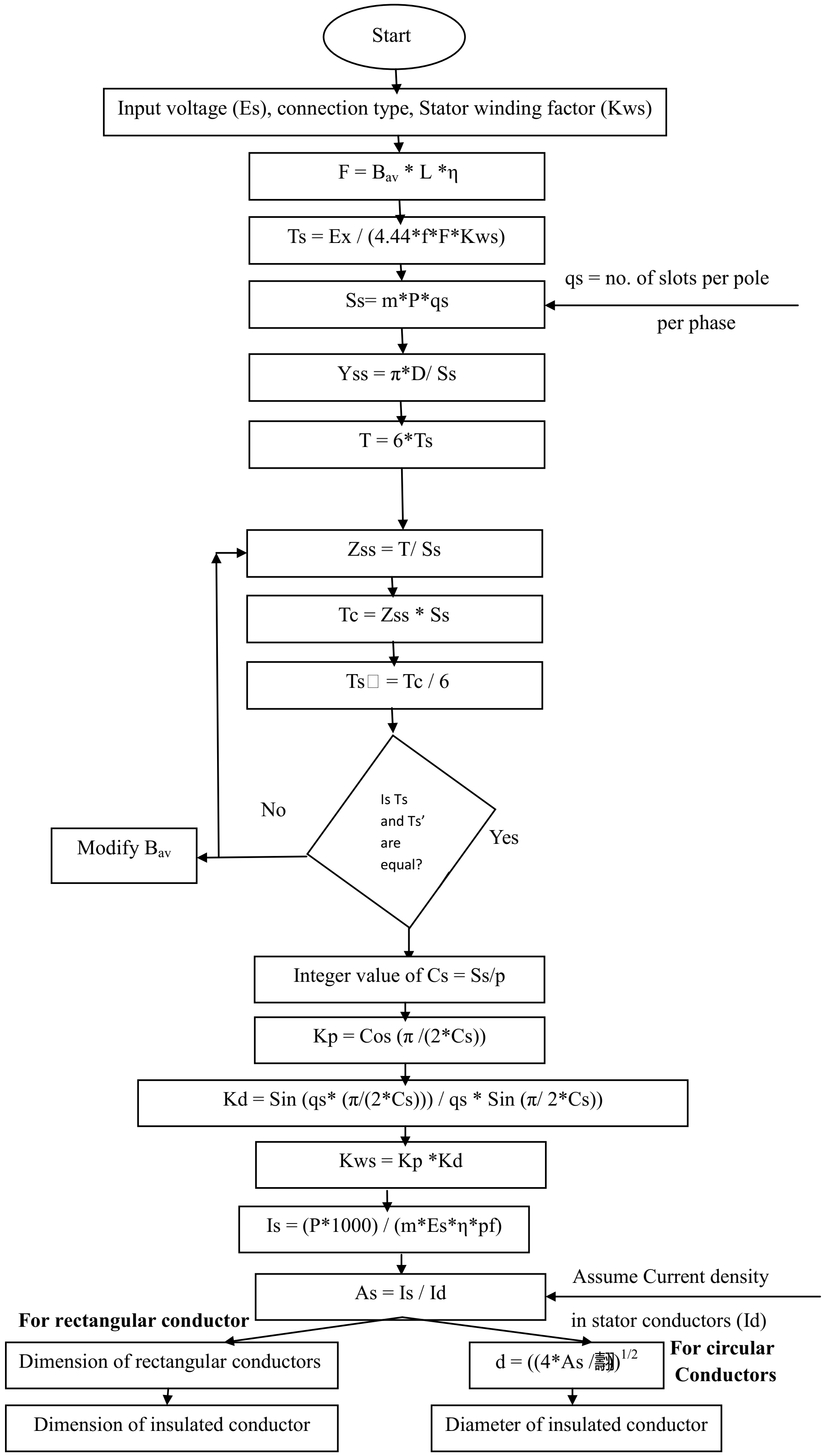
Flux in the stator core, $\Phi_c = \Phi_m / 2$

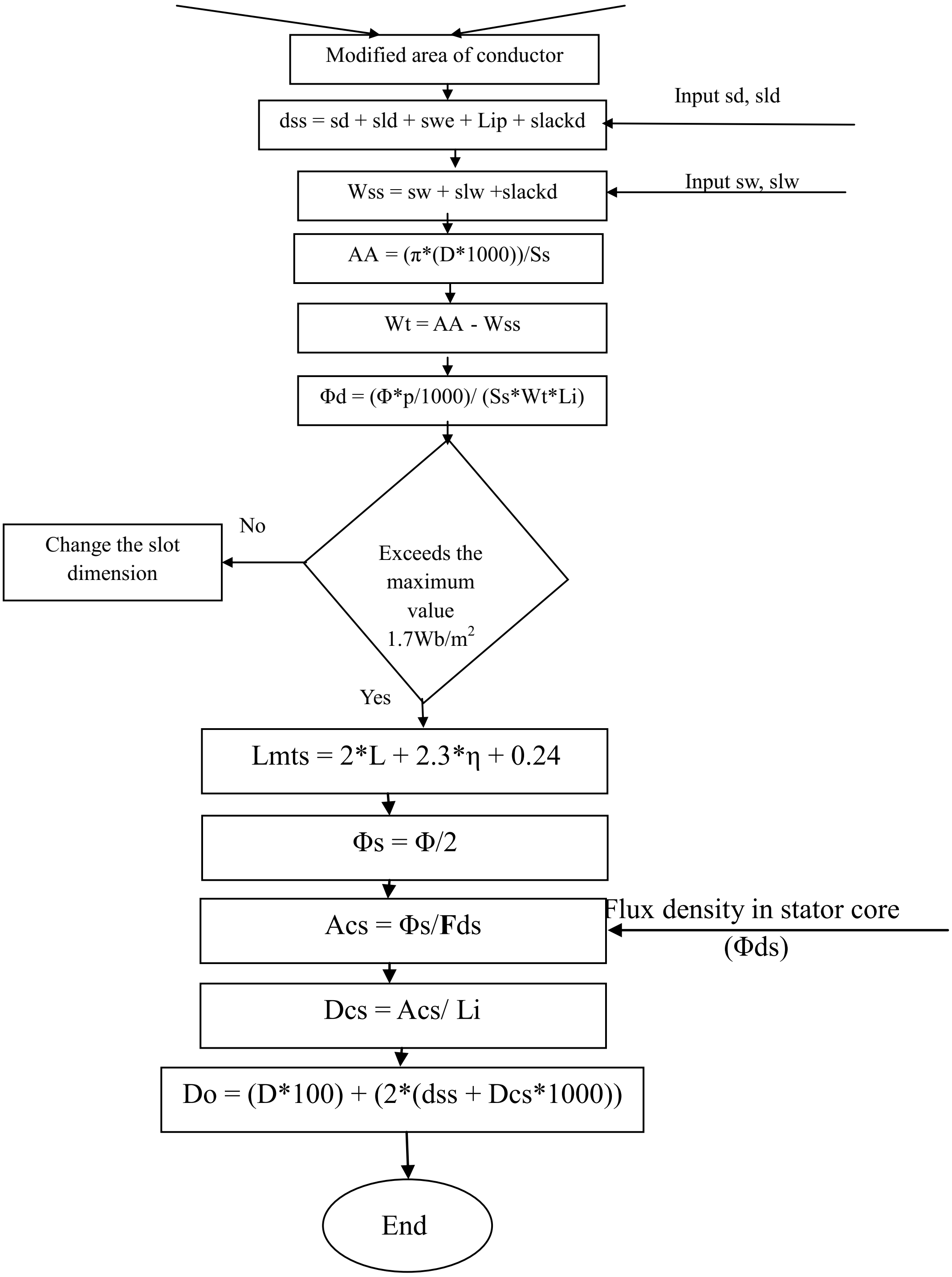
& Flux density in the stator core, $B_{cs} = \Phi_m / (2 \times L_i \times d_{cs})$ **UNIT-IV**where, d_{cs} = depth of stator core

UNIT-IV

Q. 7: With the help of flow chart explain the computer based stator design of 3-phase induction motor.

Sol: The flow charts of stator design of 3-phase induction motor is as under.Start **Stator Design:**





where, sd = no. of conductor in depth.

sId = insulation along depth of the conductor.

sw = no. of conductor in width

sIw = insulation along width of the conductor.

Q. 8: What is Computer Aided design for machines? Discuss and compare the analysis and hybrid methods for design purpose.

Sol: Computer-Aided design: The design of electrical machine (including transformers) consist essential solutions of many complex and diverse engineering problems and these problems are interrelated to each other. Thus, the electrical machine design is a mathematical indeterminate problem with many solutions, as number of unknowns is greater than the no. of equations. But the machine design can be achieved by correct decisions based upon the judgement and intuition and very clear understanding of the project. In today's world, the prime endeavour of an electrical machine lies in designing the machine suited to the work place, such as:

a) Good performance that fits into the technical specifications.

b) Permissible cost of the machine.

c) Satisfactory life of the machine in comparison to the cost.

d) Higher operating range and suitable for multi-tasking.

e) Easy maintenance and simple in construction.

The manual design procedure of a machine is very time consuming and tedious work, needs more man power and less accuracy. Further, during the manual design, lot of approximations are required to be considered which gives inaccurate results. Thus, we can use a so-called computer language to solve the above mentioned problems and thus this approach is called as **Computer aided electrical machine design**.

The process of design of a single electrical machine may be divided into three major design problems:

i) Electromagnetic design

ii) Mechanical design

iii) Thermal design

The above problems can be solved separately and the results thus obtained, are combined later on. Additionally, each of these problems may be subdivided into simple but loosely related elements. Each element is considered as a separate problem and thus the solution can be found out as an acceptable solution.

The other aspect of the present day design of electrical machines is designing a set of machines, all of which form a part of a single system. The different machines connected in such a system react upon each other, sometimes considerably and on occasions drastically. So, the machines require to operate on a system cannot be designed for isolation and thus the designs of all such machines have to be completed concurrently since the design of one machine is closely related to the design of other machines. Thus for these problems, optimization techniques are required for.

It is often desired to design a series of machines having different ratings to fit into a given frame size. In this case, the machines over a range of ratings use the same given frame size. In this case, the machines over a range of ratings use the same diameter (D) but different core lengths (L) to achieve the required outputs. In this case, the finished designs of machines must be produced in groups, where all the designs within a group are interdependent.

It takes many iterations to arrive at an optimal solution. The iterations require changes of values of variable for cost as well as performance constraints are achieved.

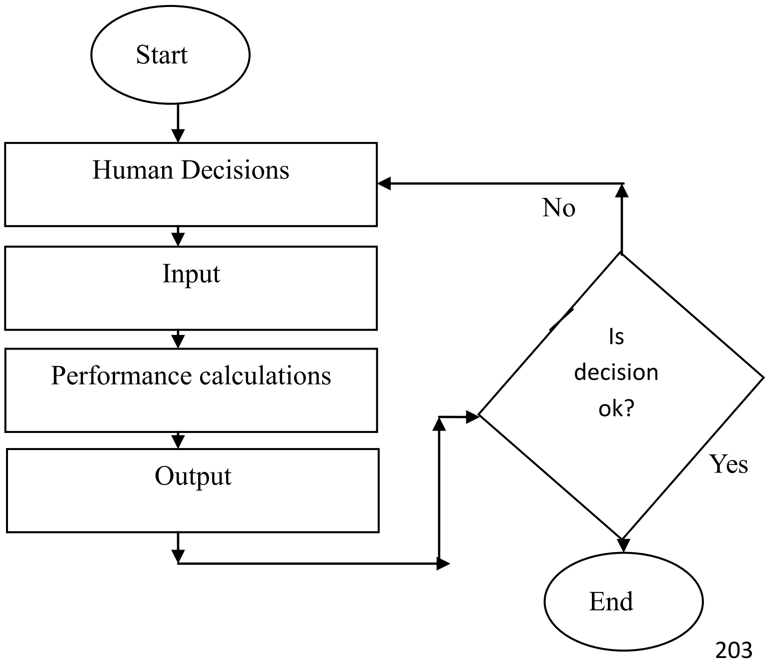
Thus, at last, it can be stated that the design of electrical machines is an iterative process wherein the assumed data may have to be varied many a times to arrive a desired design. Thus, due to above factors and circumstances, wide spread use of digital computers for design of electrical machines.

Techniques of Optimization: There are two commonly acceptable optimization approaches to machine design, namely:

i) Analysis method and ii) Synthesis method.

i) Analysis Method: The analysis method of design is depicted as in fig. In this method, the choice of dimensions, materials and type of construction are made by the designer and these are presented as input data to the computer. The performance was calculated by the computer and is returned to the designer for examination. The designer examines the performance and makes choice of input, if necessary and performance is recalculated. This procedure is repeated till the performance requirements are satisfied.

The use of term ”analysis method” means the use of computer for the purpose of analysis leaving all exercises of judgement to the designer.



The advantages of analysis method are:-

i) Easy to program, to use and to understand.

ii) It results in time saving thereby giving quick returns on investments.

iii) Programs are simple.

iv) Highly acceptable results of analysis method by the designers.

I) Hybrid Method: This method incorporates both the analysis as well as synthesis methods in the program. Since the synthesis methods involve greater cost, the major part of the program is based upon the analysis with a limited portion of the program being based upon synthesis.

Electrical Machine Design

SOLVED QUESTION PAPER-10

Note: Attempt *Five* questions in all, selecting at least one question from each unit. Assume any missing data if required.

UNIT-I

Q. 1: Discuss the general features and limitations in the designing of rotating electrical machines.

Sol: General features of electrical machine design: Design may be defined as a creative physical realization of theoretical concepts. Engineering design is application of science, technology and innovation to produce machines to perform specified tasks with optimum economy and efficiency.

The problem of design and manufacture is to build, as economically as possible, a machine which fulfils a certain set of specifications and guarantees. Thus, the major considerations to evolve a major design are:

1. Cost, 2. Durability, 3. Compliance with performance criteria as laid down in specifications.

A good design is one where is the machine has reasonable operating life and has a low initial cost. A design process is not merely engineering calculations bur involves careful consideration of the followings.

1. **Design base**: Matching the existing experience with Research and Development, bringing in the latest material technology, convenience in production line and transportation, working safely and reliability, maintenance and repair, environmental conditions, cost economy, optimization.

2. **Specifications**: Meeting with customer's requirements, guarantees, satisfy the national and international standards.

3. **Design Transfer**: Transfer of design to factory foremen, i.e. drawings, processes, instructions, job-flow, meeting with delivery schedule.

4. **Information updating**: Technical journals, R & D papers and reports, interaction in meetings and seminars.

Knowing the characteristics and specifications that a machine has to satisfy, the main areas of design are:-

a. The magnetic circuits: core yoke and air gap.

b. The electric circuit- windings

c. The insulation.

d. Heating and cooling circuits.

e. The mechanical constructions.

Moreover economy in manufacturing costs, operating and running costs of the machine is also kept in view.

Limitations in electrical machine design: Apart from availability of suitable materials, facilities available for manufacture of required machine parts and facilities required for transportation, the following considerations impose the limitations in design:

a. **Saturation of magnetic parts:** Electromagnetic machines use ferro-magnetic materials. The maximum allowable flux density to be used is determined by the saturation level of the ferro-magnetic material used. Thus, this leads to higher core losses and increased excitations.

b. **Temperature rise:** The most vulnerable part of the machine is insulation. The operating life of the machine depends upon the type of insulating materials used in the construction of the machine and life of insulating materials in turns depends upon the temperature rise of the material. Thus, increase in temperature rise, deteriorates the insulation and affects the life of the machine.

c. Insulation: The insulation materials used in a machine should be able to withstand the electrical, mechanical and thermal stresses which are produced in the machine due to high voltage gradient and under short-circuit conditions. Thus the insulation breakdown due to electrical and thermal breakdown considerations.

d. Efficiency: The efficiency of the machines should be as high as possible to reduce the operating cost. Thus, it requires the use of large amount of material, both iron and copper. So, the capital cost of the machine designed with high efficiency is high.

e. Mechanical parts: The construction of an electrical machine has to satisfy numerous technological requirements. The construction should be as simple as possible and also it should be good. Thus, the design of mechanical parts is particularly important in the case of high speed and large size machines. In induction motors, the length of air gap is as small as mechanically possible in order to have a high power factor. The length of air gap and also that of the size of the shaft are mainly decided by the mechanical considerations. The size of the shaft should be such that it does not give rise to excessive magnetic pull when deflected.

f. Commutation: The problem of commutation is important in the use of dc machines. Thus due to commutation, the output power of machine is limited.

g. Power factor: Poor power factor results in larges values of current per phase for the same power and thus, larger conductor size have to be used. As in case of induction motors, the size and hence cost of machines can be reduced by using a high value of flux density in the air gap but this makes the saturation of iron parts and thus a poor power factor. So, the value of flux density used depends upon the power factor and hence power factor becomes a limiting factor.

h. Customer's specifications: The limitations imposed by the customer's specifications on the design of machines are obvious, as due to economic constraints and specifications as laid down in the customer's orders.

I. Standard specifications: These specifications are the biggest strain on the design because both the manufacturer and the customer cannot get away from them without satisfying them.

Q. 2: Derive the output equation for DC machine. Discuss the selection of poles and speed.

Sol: Output equation of DC machines: The output equation of an electrical machine can be expressed in terms of its main dimensions, specific magnetic and electrical loadings and speed, the equation describing this relationship is as output equation.

<u>DC Machine</u>:

As power developed by armature in kW,

P_a = generated emf x armature current x 10^{-3}

But, $E = \Phi Z n p / a$

So, $P_a = \Phi Z n p / a \times I_a \times 10^{-3}$

$P_a = (p \Phi) [(I_a / a) \times Z] n \times 10^{-3}$

$P_a = (p \Phi) [I_z \times Z] n \times 10^{-3}$

$$P_a = \text{(total magnetic loading) x (total electrical loading) x n x } 10^{-3}$$

Here, specific magnetic loading, $B_{av} = (p \Phi) / (\pi D L)$ = (Total flux / area of each pole)

So, $\mathbf{p \Phi = B_{av} \times (\pi D L)}$

& specific electric loading, $ac = (I_z \times Z) / (\pi D)$

= total ampere conductor / perimetry of armature

So, $\mathbf{(Iz \times Z) = ac \times (\pi D)}$

Thus, power developed by the armature is, $\mathbf{P_a = C_o . D^2 . L . n}$ $P_a = (1.11\pi^2 B_{av} \times ac \times 10^3) D^2 L n$

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

&

output coefficient, $C_o = 1.11\pi^2 x\ B_{av}$ x ac x10^3

This is called as output equation of the dc machine.

Selection of number of poles: The value of the output coefficient C_o can be obtained after suitable choice of values of B_{av} and ac and then the value of power output is obtained.

Output power developed by the armature, $P_a = C_o. D^2.L.n$

& output coefficient, $C_o = \pi^2. B_{av}. ac. 10^{-3}$

It now remains to select appropriate values of D and L which corresponds to the calculated value of D^2L. In order to obtain suitable proportions for the machine, it is necessary to consider both the magnetic as well as electric loadings. So far as, the magnetic circuit is concerned, it is necessary to choose suitable number of poles and also to suitably proportion them. The number of poles used in a dc machine has an important bearing upon both the magnetic and electric circuits. For the choice of poles, let the length, diameter of machine, the specific magnetic and electric loadings are fixed and number of poles can be varied as:

Φ_T = Total flux around the air gap = $p\ \Phi = B_{av} \times \pi\ D\ L$.

& AC= Total ampere conductors over the armature periphery = $I_z \times Z = (I_a/a)\ Z = ac.\ \pi.\ D$

are both constant.

Speed: Speed/ frequency of the flux reversal in dc machine is given by, f = p. n/2.

So, if we chose a large no. of poles, the frequency is high. The frequency of alternations of magnetic flux in dc machines should not be very high as it would give rise to excessive iron losses in the armature core. Generally, the value of frequency f lies between 25-50Hz, but may be more in small machine, typically high speed series motor designed with a low air gap density.

UNIT-II

Q. 3: Design a 250kVA, 2000/400Volt, 50Hz, 1-phase core type oil immersed self cooled transformer with the following data:

Induced flux density in the core = 1.25Wb/m^2

Current density = 2.75 A/mm^2

Window space factor = 0.3

Ratio (window height / window width) = 3

Three stepped core. The net iron area is 0.6d^2 in the stepped core where d is diameter of circumscribing circle. The width of largest stampings is 0.9d. Assume three stepped construction for yoke.

Sol: Given that, kVA rating = 250kVA

$V_1 = 2000V$

$V_2 = 400V$

f=50 Hz, 1-phase core type transformer

$B_m = 1.25 Wb/m^2$

Current density, $\delta = 2.75\ A/mm^2 = 2.75 \times 10^6\ A/m^2$

Window space factor, $K_w = 0.3$

3-stepped core is used with iron area, $A_i = 0.6d^2$

As assume, **emf per turn, $Et = 4.44 f B_m A_i = 15V$**

So, net iron area, $A_i = E_t / 4.44 f B_m = 0.05405m^2$

As given, $A_i = 0.6 d^2$

So, diameter of circumscribing circle, d =0.30m

& **width of the largest stampings, a = 0.9d = 0.9 x 0.30 = 0.27m**

As per the output equation of 1-phase core type transformer,

$$Q = 2.22 f B_m A_i A_w K_w \delta \times 10^{-3}$$

or, $250 = 2.22 \times 50 \times 1.25 \times 0.05405 \times A_w \times 0.3 \times 2.75 \times 10^6 \times 10^{-3}$

or, **$A_w = 0.04040m^2$**

As given, window height, h_w / window width, $W_w = 3$

& area of window, $A_w = h_w \times W_w = 0.04040$

So, **width of window, $W_w = 0.116m$**

& **height of window, $h_w = 0.348m$**

As given 3-stepped core for yoke,

So, **height of yoke $h_y = a = 0.27m$**

& **depth of yoke, $d_y = a = 0.27m$**

Overall dimensions:

Overall height, $H = h_w + 2 h_y = 0.348 + 2 \times 0.27 = 0.888m$

Overall width, $W = D + a = W_w + d + a = 0.116 + 0.30 + 0.27 = 0.686m$

Q. 4: Discuss the construction details of low speed and turbo generators. Discuss the selection of electric loading in each case.

Sol:

Construction of Low speed Hydro-generators: The constructional features of hydro-generators are basically dependent upon the mechanical considerations which depend upon the speed of the machine. The hydro-generators are low speed machines, the speed depending upon the available water head and type of turbine used. The low speed demands a multi-polar construction and consequently a large diameter is needed. The turbine governing or transient stability of the network to which the generator is connected, is dependent upon the total inertia of turbine and the generator & thus, the rotor of generator must be designed to give requisite inertia.

a) Stator Core: The stator core is built up of laminations in order to reduce the eddy current iron losses. Thus the design of stator core depends on choice of the type and grade of steel. So, in initial stage, hot rolled steel were used for stator core. These laminations had many imperfections such as variation in thickness of laminations between individual sheets. Thus this gives unequal lengths of core along different points on the periphery. So, to ensure a tight core, a very high axial clamping pressure had to be used and these high pressures require a high clamping structure. So, after that, cold rolled grain oriented (anistropic) sheet steel is preferred to fabricate the stator core. This material has directional properties that give low specific iron losses when the flux is parallel to the direction of rolling. Thus, the magnetization is very low along parallel to the direction of rolling and very much higher along right angles to this direction. The modern synchronous machines use non-directional cold rolled steel which has electrical characteristics but improved mechanical characteristics to the hot rolled steel, like uniformity of thickness of laminations, smoothness of surface of laminations, higher fatigue, strength and lower clamping pressure.

The commonly used grade of steel for stator core laminations is 0.5mm thick. The laminations are insulated with paper stuck on one side or enamel for insulation.

The stator laminations are either punched as a complete circle or are in the form of segments, as shown in fig. in case the diameter is large. The maximum width of standard sheet steel is 1metre which represents as the diameter for a complete circle. Since the outside diameter of all large hydro-generators are much greater than 1meter, thus the laminations are made in segments. The number of segments per circle varies from 6 to 42 and it depends upon the size of slots and number of stator sections.

The outside diameter of all practically used hydro-generators in generating stations is usually exceed 3.5m to as high as 18metre. Thus in order to facilitate handling in the factory and to relieve from the problem of transportation to site for erection and installations, the stator core and frame are divided into equal segments, which can be 2 to more in number.

b) Stator winding: The stator winding of all synchronous generators is star connected with neutral earthed. This arrangement has the advantage that the winding has to be insulated to earth for the phase voltage. Star connection also eliminates the triplen harmonics in the generated line voltage. The present practice is to use double layer lap or wave windings with 60^0 phase spread. Fractional slot windings are used to reduce the higher order harmonics in the generated line voltage, such as 5^{th} and 7^{th} order harmonics.

The windings may have multi-turn coils, single turn coils or bar windings. High voltage machines having a large number of poles have a large number of turns and so, multi-turn coils are used in these machines. Whereas in low voltage machines, a smaller number of turns are required and thus, bar type windings are preferred. The multi-turn coils are machine made whereas the bar windings are made by hand.

In case of bar winding, the stator winding is designed as a bar winding having two bars in each slot. Thus the bar consists of a large number of conductors insulated from each other and connected to each other in parallel. The conductors are put in two layers along with width of stator slot. The bars are transpositioned to reduce the eddy current losses in the conductors.

The bar windings has many advantages as compared with multi-turn coil windings. These are:

1. In a multi-turn coil, there are many turns in each coil side while in a bar winding, one turn per coil side. So, in addition to the main insulation to earth, each turn of multi-turn coil requires individual insulation in order to provide sufficient dielectric strength to withstand impulse strength. Whereas in bar winding with two bars per slot, the inter-turn insulation is twice as thick as the main insulation to earth, thus, no special precautions are necessary.

2. In bar winding with wave windings avoids the use of a large number of connectors and is particularly useful for machines with a large number of poles.

The advantages of a winding with multi-turn coils are:

1. These windings allow greater flexibility in selecting the value of stator slots to give a required number of turns per phase.

2. Since, the coils are machine made, thus they are cheap.

c) Bracing of Stator Overhang portion: Electromagnetic forces are produced in the stator overhang portions of windings due to interaction between conductors carrying current in the same direction and due to repulsion between conductors carrying in opposite conductors.

Under normal conditions, the electromagnetic forces produced by the current carrying conductors are negligible. But during sudden short-circuit at the line terminals, the current in the windings may rise to about 15 times the full load current and the electromagnetic forces, may rise to 250 times the force under normal full load conditions. These forces are either tangential or radial. Thus due to these forces, overhand portion tend to pull the stator conductors outwards and thus there will be cracking in the insulation at the core ends. Thus, **the conductors in the overhang must be braced, i.e. their mechanical strength are raised**.

d) Rotor body: The salient poles are attached to the rotor body. **The type of rotor body used depends on the peripheral speed of the machine**. The body is:

i) machined with its shaft from a forging.

ii) built up from discs on the shaft.

iii) fabricated from cast-steel spider mounted on the shaft and carrying laminar ring.

The forged steel construction is used for high speed machines, due to high tensile strength. However the cost of forging and its machining is high and thus cannot be used for machine with larger diameter.

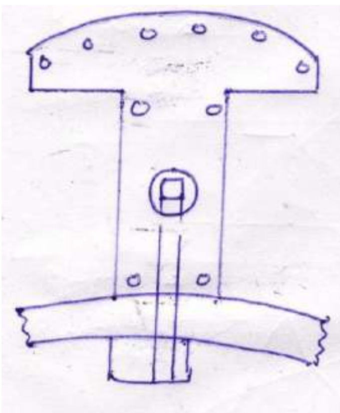
Another type of construction employs thick rolled steel discs, 120-1800mm in length either shrunk on the shaft and formed into a solid ring by axial through bolts. This construction is cheaper and thus it is used for generators running at 600rpm and above and upto a peripheral speed of 190m/sec.

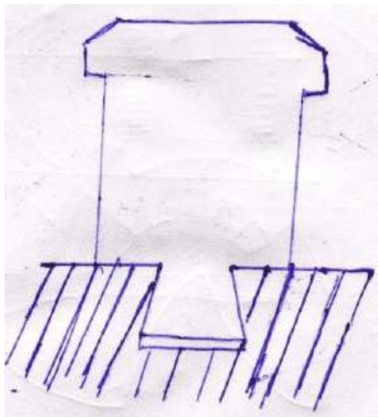
Another construction form of rotor body is the punched segmental rim carried on a fabricated steel spider mounted on the rotor shaft. The laminations are 1.6mm thick and are in the form of overlapping segments tightly bolted. Thus the spider is free from all electromagnetic forces other than due to its mass and so, produces the torque to the shaft. This type of construction can be used for peripheral speed of 130m/sec. The advantages of a segmental shaft are that it is easy to fabricate and transport & assembled at site.

e) **Poles**: The poles are clamped or fixed to the rim/shaft in different ways. In case of generators with peripheral speed upto 25m/sec., the poles are bolted to the yoke as shown in figs. The attachment of poles to the periphery of the wheel is done by studs inserted from the underside of the rim.

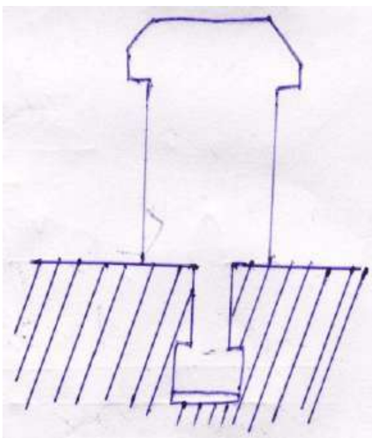
In the case of water wheel generators having peripheral speed between 20 to 80m/sec., either the dove tail or the T-head type of construction is used for fixing the poles to the yoke.

The cross-section of poles may be rectangular or circular. The circular cross-section can only be used only if the poles are massive.





Types of Poles in Hydro generators



Types of Poles in Hydro generators (contd.)

a) Field windings: in hydroelectric generators, the so called "strip or edge" winding is used for the field coils. The field coils are formed from a flat copper strip wound edgewise with inter-turn insulation on a machine operate former. The coils are then cured and consolidated under a pressure exceeding due to centrifugal forces on the coils.

The coils may have a smooth surface or may have some of the turns made of wide copper strap, so that these can act as cooling fins. Thus these lowers the temperature rise in the machine.

b) Damper windings: In synchronous generators, damper winding is provided to suppress the negative sequence field and to damp out the oscillations during hunting. For synchronous motors, the damper winding has different purpose: it is provided i) to start the motor and ii) to damp out the oscillations and to develop the damping power during hunting.

The damper windings are housed in the pole shoes. These damper windings consist of heavy copper rods, one in each slot or hole riveted at the ends of common bars one at each end so as to form short circuited grids or end bars. These short-circuiting end bars are carried right around the rotor so that they form two short-circuiting rings around the periphery. This coverts damper winding into a cage winding.

The damper windings are subjected to considerably high centrifugal forces as the peripheral speed of synchronous machine is very high. So, special attention must be paid to connecting bars in the rotor.

c) Bearings: The bearings for horizontal shaft hydro-generators are of conventional type as ball bearings or roller bearings. In the case of vertical shaft hydro-generators, special features have to be incorporated in the bearing set up because the requirements of rotor and the turbine runner. Oil is employed to the bearings by pumps and cooled externally.

d) Slip Rings: The slip rings are required to supply excitation to the field winding. The slip rings are made of steel and are shrunk over the cast iron with insulation between the two.

Construction of Turbo-alternators: All modern turbo-alternators are 2-pole machines and their speed is 3000rpm corresponding to a frequency of 50Hz.

Turbo-generators are characterized by long lengths and short diameters. This is because it is not possible to increase the diameter beyond a certain limit (1.2m) due to mechanical considerations like centrifugal forces, deflection of shaft and the critical speed. Thus, the rating of these machines can be increased only by an increase in the axial core lengths per MVA.

With large axial core lengths, it is very difficult to cool the machine, especially at centre portions of the machine. In fact, the cooling of turbo-generators is one of the most complex engineering problems.

a) Stator core: The stator core is built up with the same methodology of the construction of stator core of hydro-generators. The use of grain oriented steel laminations with the direction of flux along the grains in the armature core and perpendicular to the teeth, results in the reduction of core losses.

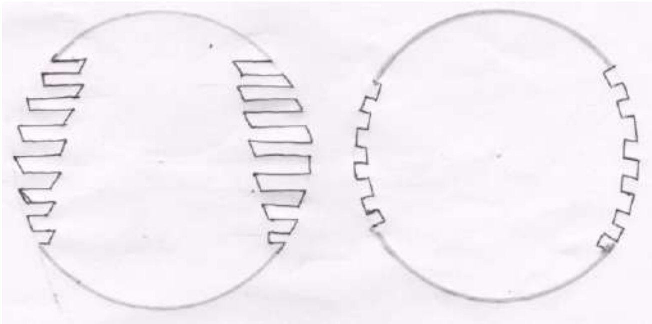
b) Stator Winding: The windings of small turbo-generators are designed to generate a voltage of some standard system level, upto 11kV. For large machines which are permanently connected to the power system through a transformer, the choice of machine voltage is left to the designer. Both the high voltage and low voltage generators have their special features. A generator with high voltage has small current but requires a thicker slot insulation, whereas low voltage generator has high currents which produce the large pulsation forces between the conductors which may be 80kN/m of conductor length for a 500MW generator. Also for large current machines, requires the use of multi-circuit windings and also the use of laminated and transposed conductors to decrease the eddy current losses.

The stator windings designed for high voltage no doubt requires a high level of slot insulation but permits the use of smaller size conductors with lesser number of parallel circuits, smaller pulsation forces between conductors, lesser conductor subdivision and ease in coil formation and installation.

The electromagnetic forces developed in turbo-alternators under short-circuit conditions are very high. Thus problem of bracing the overhang portion to withstand the forces are more acute in these machines. Therefore, **the overhang has to be highly reinforced in turbo-alternators.**

c) Rotor: The cylindrical or non-salient pole rotor is adopted for these machines, the field winding being distributed in slots, instead of being concentrated wound on the field poles. The rotor is generally made up of chromium-nickel steel or chromium- molybdenum steel. The rotor consists of a core and a shaft forged in one piece.

Slots are milted in the rotor for inserting and securing the field windings. Rotors are either radial slots or parallel slots on rotor as shown in fig.



Usually the radial slot construction is used in the turbo-generators. Generally two thirds of rotor is wound and the rest one third is left without slots to create poles. The unwound portion forms the so called large tooth through which the main flux passes. The slots have equal width throughout their depth and the rotor teeth are tapered. The teeth have minimum area of cross-section at the bottom and thus mechanical stresses are in limit. Concentric multi-turn coils are accommodated in slots. At the end of each slot a ventilating duct may be used for providing a passage for cooling air.

The end connectors (overhang) of the field winding must be rigidly supported by end bells due to large centrifugal forces at high speeds.

Choice of specific electric loading: Some of the factors that influence the choice of average gap density. These factors along with some additional factors which are specific to choice of average flux density for synchronous machines are:

1. Copper loss & temperature rise: A high value of ac leads to a high value of copper losses with decease in efficiency and increase in temperature rise. The value of ac also depends upon the cooling techniques employed. So, a lower value of ac should be used in the machines that effectively dissipate the heat

2. Voltage: A higher value of ac can be used for low voltage machines since the space required for insulation is small.

3. Synchronous reactance: The value of ac affects the syn. reactance and armature reaction in the machine. A high value of ac leads to high value of leakage reactance and armature reaction and thus a high of syn. reactance. So, the machine has poor voltage regulation, low current under short circuit conditions and a low value of steady state stability leads to instability.

4. Stray load loss: The stray load loss increase steeply with an increase in ac.

Following are the usual values of specific electric loadings used in the synchronous alternators:

Salient pole generators (Hydro-generators) = 20,000 to 40,000 A/ m.

Turbo-generators = 50,000 to 75,000 A/ m.

UNIT-III

Q. 5: What specifications are required for initiating the design procedure of induction machine? Develop the output equation for 3-phase induction motor. Explain the separation of D (bore dia.) and L (axial length). What should be the size of end rings in comparison to the size of rotor bars?

Sol: Standard specifications of 3-phase induction motor: The main specifications of a 3-phase induction motor for design purpose are:

1. Rated Output in H.P. or kW.
2. Three phases.
3. Frequency in Hz = f.
4. Voltage in Volts = V
5. Connections: Star Y or Delta Δ

6. Speed in RPM = N
7. Type: Squirrel Cage rotor or Wound rotor.
8. Type of duty.
9. Power factor
10. Efficiency.
11. Class of insulation.
12. Temperature rise.
13. Full load current.
14. Pull out torque.

Output equation of induction machine: The output equation of an electrical machine can be expressed in terms of its main dimensions, specific magnetic and electrical loadings and speed, the equation describing this relationship is as output equation.

AC Machine:

Consider an 'm' phase machine having one circuit per phase. kVA rating of the machine is,

kVA, Q = no, of phases x output voltage per phase x current per phase x 10^{-3}

$Q = m\, E_{ph}\, I_{ph} \times 10^{-3}$

We have,

Induced emf per phase, $E_{ph} = 4.44\, f\, \Phi\, T_{ph}\, K_w$

So, kVA, $Q = m \times 4.44\, f\, \Phi\, T_{ph}\, K_w \times I_{ph} \times 10^{-3}$

But, $f = p\, n_s / 2$

So, kVA, $Q = m \times 4.44\, (p\, n_s / 2)\, \Phi\, T_{ph}\, K_w \times I_{ph} \times 10^{-3}$

or, kVA, $Q = 1.11\, K_w\, (p\, \Phi)\, (2\, m\, T_{ph}\, I_{ph}) \times n_s \times 10^{-3}$

As considered, there is only one circuit per phase, so $I_s = I_{ph}$

So, total number of armature conductors, Z = no. of phases x (2 x no. of turns per phase)

or, $Z = m \times (2\, T_{ph}) = 2\, m\, T_{ph}$

& total electric loading $= I_s\, Z = 2\, m\, T_{ph}\, I_s$

Hence,

kVA, $Q = 1.11\, K_w\, (p\, \Phi)\, (I_s\, Z) \times n_s \times 10^{-3}$

or, kVA, $Q = 1.11\, K_w$ (total magnetic loading) (total electric loading) (syn. Speed) x 10^{-3}

But, $p\, \Phi = \pi\, D\, L\, B_{av}$, $I_s\, Z = \pi\, D\, ac$

Thus,

kVA, $Q = 1.11\, K_w\, (\pi\, D\, L\, B_{av})\, (\pi\, D\, ac) \times n_s \times 10^{-3}$

or, kVA, $Q = (1.11\, \pi^2 K_w\, B_{av}\, ac \times 10^{-3})\, D^2\, L\, n_s$

or, kVA, $Q = (11\, K_w\, B_{av}\, ac \times 10^{-3})\, D^2\, L\, n_s$

or kVA, $Q = C_0\, D^2\, L\, n_s$

$$\mathbf{Q = C_o .\, D^2 . L . n}$$

&

Output coefficient, $C_o = 1.11\pi^2 x\ B_{av}$ x ac x10^3 = 11 B_{av} x ac x10^3

This equation is known as output equation of the ac machines.

Main Dimensions: The product D^2L obtained from the output equation is split up into two components D and L. The separation of D and L for various design features for induction motors is based on ratio of core length L to pole pitch ($\tau = \pi D/p$) i.e. L/τ.

Minimum cost = 1.5 to 2

Good power factor = 1.0 to 1.25

Good efficiency = 1.5

Good overall design = 1.0

For best power factor, $\tau = \sqrt{(0.18 L)}$

For small motors, high values of L/ τ results in small diameters. **In general, the value of L / τ lies between 0.6 and 2 depending upon the size of machine and the characteristics desired**.

Area of Rotor bars: The performance of an induction motor is greatly influenced by the resistance of the rotor. A motor designed with high rotor resistance has the advantage of high starting torque, however, has a disadvantage of higher I^2R losses and thus its efficiency is lower under running conditions.

The value of rotor resistance depends upon the current density used for rotor conductors. The higher is the current density, lower is the conductor area and thus the resistance of rotor increases. The rotor resistance is the combination of resistance of rotor bars and rotor end rings. The cross-section of the bars and the end rings must be so selected that a proper value of resistance is obtained i.e. a value of rotor resistance which meets the both requirements of starting torque as well as the efficiency.

Current density in the rotor bars δ_b may be taken between 4 to 7A/mm^2.

So, **Area of rotor bar, $a_b = I_b / \delta_b$ mm^2**

where, **I_b = Current in rotor bars = 0.85 x ($6\, I_s T_s / S_r$)**

Area of End Rings: The value of current density chosen for the end rings should be such that the desired value of rotor resistance is obtained.

The ventilation is generally better for end rings and so, a higher value of current density can be taken than that of rotor bars.

So,

Area of rotor end rings, $a_e = I_e / \delta_e$ mm^2 = $S_r I_b / \pi p S_e$ mm^2

& **I_e = Current in rotor End rings = $S_r I_b / \pi p$**

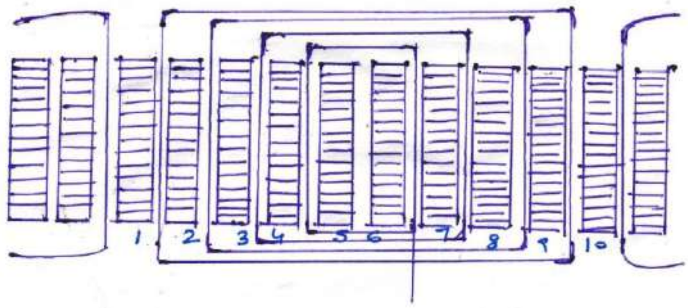
Q. 6: Discuss the design procedure to estimate the dimensions of main windings in single-phase induction motor. What is the criteria for the selection of rotor slots? Explain the check for flux density in the stator teeth. Discuss the way to increase the starting torque.

Sol: Design of Running winding (main winding): The stator windings of a single-phase induction motors are concentric type. There are usually 3 or more coils per pole each having same or different number of turns.

The arrangement of winding is governed largely by the necessity of minimizing harmonic fluxes which may otherwise give rise to noise and uneven accelerating torque. Such harmonics produce non-sinusoidal shape of mmf wave. Mmf wave harmonics can be reduced by utilizing 70 percent of the total slots for the running winding as this arrangement gives minimum low order harmonics. The remaining slots (30 percent) are used for accommodating the starting windings.

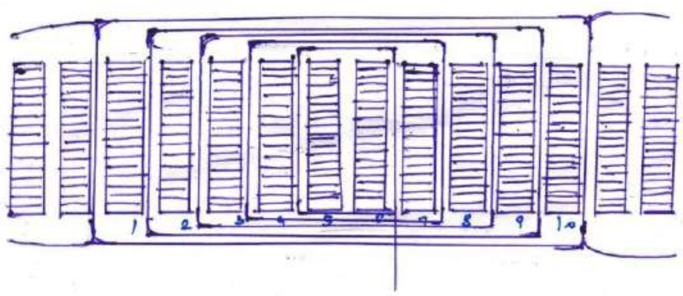
In a small single-phase induction motor may be desirable to reduce the harmonics still further by grading the winding i.e. by having different number of conductors in each slot thereby giving an mmf wave which becomes nearly sine wave.

Let the winding arrangement for an induction motor as shown in arrangement with 9 stator slots per pole. There are 4 coils per pole:



Coil (1-9)	-	it spans 8 slots
Coil (2-8)	-	it spans 6 slots
Coil (3-7)	-	it spans 4 slots
Coil (4-6)	-	it spans 2 slots

The coils can be re-arranged as shown in fig. below with again 4 coils per pole,.



Coil (1-10)	-	it spans 9 slots
Coil (2-9)	-	it spans 7 slots
Coil (3-8)	-	it spans 5 slots
Coil (4-7)	-	it spans 3 slots

With this arrangement the number of turns are lying of one side of the pole and other coil side on the other side of pole.

a) Number of turns of Running Winding: The number of turns in the stator running winding can be calculated as follows:

Stator Induced voltage, $E = 4.44\, f\, \Phi_m\, T_m\, K_{wm}$

where, T_m = no, of turns in running winding

K_{wm} = winding factor for running winding

So, number of turns on running winding T_m,

$$\mathbf{T_m = E / 4.44\, f\, \Phi_m\, K_{wm}}$$

& $\quad \mathbf{\Phi_m = Bav \times (\pi DL / p)}$

The value of stator induced voltage E is equal to 85 percent of supply voltage V. The winding factor for the running winding can be assumed between 0.75 to 0.85.

Number of turns in series per pole for the main winding,

$$\mathbf{T_{pm} = T_m / P}$$

a) Running winding conductors: Current carried by each running winding conductors,

$$I = h.p. \times 746 / (V\, \eta \cos Ø)$$

Area of running winding conductor, $\mathbf{a_m = I_m / \delta_m}$

where, δ_m is the current density for running winding conductors in A/mm^2.

Selection of Stator slots: The various aspects of stator slots are to be considered for 1-phase induction motor designing, such as number of stator slots, size of stator slots, stator teeth, stator core etc.

1. **Number of stator slots**: A large number of slots reduced the leakage reactance. Thus, we can take more output from the motor frame and can have better overload capacity and better efficiency and better power factor. A large no. of stator slots also reduces the problems of harmonics and cogging.

But with large no. of slots, the space factor for slots becomes poorer, so, thus there is an upper limit for no. of slots, which in turn depends upon the size of the machine.

Thus, the number of stator slots per pole is usually between 9 to 12. For a 1-phase induction motor, the number of stator slots per poles should be real so that a regular winding is obtained.

2. **Size of Stator slots**: As the stator slots carries both running windings and starting winding conductors. The starting winding conductor has a small cross-sectional area and its effect on size of slot is small, whereas the running winding conductor with large no. of turns will determine the size of slot. **As in 1-phase induction motors, semi-closed slots are preferred, the insulation between core and coil is placed in the slots as slot lining. The slot liner is of 0.3 to 0.4mm thick**.

The ratio of insulated conductor area to the slot area should never exceed 0.5.

Let Z_s is the total no. of conductors per slot and d_1 mm is the diameter of insulated conductor.

Then, area required for insulated conductor = $Z_s \times (\pi/4)\, d_1^2$

So, Minimum slot area required = $(1/0.5) \times Z_s \times (\pi/4)\, d_1^2$

The average slot width,

$$\mathbf{W_{s(av)} = \pi (D + d_{ss}) / S_s - W_{ts}}$$

where, d_{ss} = depth of stator slot, W_{ts} = width of stator teeth**Area of each slot = $W_{s(av)} \times d_{ss}$**

S_s = number of stator slots

So, **Area of each slot = $W_{s(av)} \times d_{ss}$**

Flux density in Stator teeth: The stator tooth density B_{ts} can generally be from 1.4 to 1.7 Wb/m^2. For general purpose machines, a flux density of 1.45Wb/m^2 and for high torque machines, it may go up to 1.8Wb/m^2.

Take stacking factor, **K_s = 0.95**

So, **Net iron length, L_i = 0.95 L**

Flux density in the stator teeth,

$$\mathbf{B_{ts} = \Phi_m / ((S_s/p) \times L_i \times W_{ts})}$$

Methods of increase of starting torque:

Let,

R_m = total resistance of main / running winding = $r_{sm} + r_{rm}'$

X_{lm} = leakage reactance of main winding,

Z_m = total locked rotor impedance in terms of main winding

$= \sqrt{R_m^2 + X_{lm}^2}$

I_{sm} = current in main winding = V / Z_{sm}

θ_m = phase angle between applied voltage V and current in the main winding

$\boldsymbol{\theta_m = \tan^{-1} (X_{lm} / R_m)}$

T_m = no. of turns in main winding

K_{wm} = winding factor for main winding

T_a = no. of turns in starting/ auxiliary winding

K_{wa} = winding factor for starting winding

K = ratio of effective starting winding turns to main winding turns

or, $\boldsymbol{K = (T_a K_{wa}) / (T_m K_{wm})}$

r_{sa} = resistance of starting winding

r_{ra}' = resistance of rotor in terms of starting winding

or, $\boldsymbol{r_{ra}' = (T_a K_{wa}) / (T_m K_{wm})^2 r_{rm}' = K^2 r_{rm}'}$

R_a = total resistance in terms of starting winding

$R_a = r_{sa} + r_{ra}' = r_{sa} + K^2 r_{rm}'$

X_{la} = total leakage reactance in terms of starting winding = $K^2 X_{lm}$

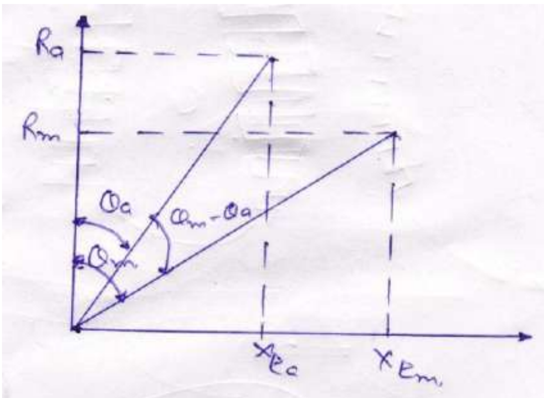
Z_a = total locked rotor impedance in terms of starting winding

$= \sqrt{R_a^2 + X_{la}^2}$

I_{sa} = current in staring winding = V / Z_{sa}

θ_a = phase angle between applied voltage V and current in the starting winding

$\boldsymbol{\theta_a = \tan^{-1} (X_{la} / R_a)}$



The starting torque in 1-phase induction motor is given as:

$$\boldsymbol{T_s = (1/2\pi) \times (p K r_{rm}' / f) I_{sm} I_{sa} \sin (\theta_m - \theta_a)}$$

Furthermore, due to magnetizing current, I_μ, the equation becomes,

$$T_s = (1/2\pi) \times (p C_r K r_{rm}' / f) I_{sm} I_{sa} \sin (\theta_m - \theta_a)$$

The value of C_r is equal to,

$$\boldsymbol{C_r = K_r / (1 + (r_{rm}' / X_{am})^2)}$$

or, $T_s = (1/2\pi) \times (p C_r K r_{rm}' / f) (V^2 / Z_{sm} Z_{sa}) \sin (\theta_m - \theta_a)$

$$\boldsymbol{T_s = (1/2\pi) \times (p C_r K r_{rm}' / f) V^2 [R_a X_{lm} - R_m X_{la} / Z_m^2 Z_a^2]}$$

UNIT-IV

Q. 7: What is computer aided design for machines? Discuss its advantages in comparison to conventional design. Give the names of software which can be used for design purpose. What is optimization?

Sol: Computer Aided Design for machines: The design of electrical machine (including transformers) consist essential solutions of many complex and diverse engineering problems and these problems are interrelated to each other. Thus, the electrical machine design is a mathematical indeterminate problem with many solutions, as number of unknowns is greater than the no. of equations. But the machine design can be achieved by correct decisions based upon the judgement and intuition and very clear understanding of the project. In today's world, the prime endeavour of an electrical machine lies in designing the machine suited to the work place, such as:

a) Good performance that fits into the technical specifications.

b) Permissible cost of the machine.

c) Satisfactory life of the machine in comparison to the cost.

d) Higher operating range and suitable for multi-tasking.

e) Easy maintenance and simple in construction.

The manual design procedure of a machine is very time consuming and tedious work, needs more man power and less accuracy. Further, during the manual design, lot of approximations are required to be considered which gives inaccurate results. Thus, we can use a so-called computer language to solve the above mentioned problems and thus this approach is called as **Computer aided electrical machine design**.

The process of design of a single electrical machine may be divided into three major design problems:

i) Electromagnetic design

ii) Mechanical design

iii) Thermal design

The above problems can be solved separately and the results thus obtained, are combined later on. Additionally, each of these problems may be subdivided into simple but loosely related elements. Each element is considered as a separate problem and thus the solution can be found out as an acceptable solution.

The other aspect of the present day design of electrical machines is designing a set of machines, all of which form a part of a single system. The different machines connected in such a system react upon each other, sometimes considerably and on occasions drastically. So, the machines require to operate on a system cannot be designed for isolation and thus the designs of all such machines have to be completed concurrently since the design of one machine is closely related to the design of other machines. Thus for these problems, optimization techniques are required for.

It is often desired to design a series of machines having different ratings to fit into a given frame size. In this case, the machines over a range of ratings use the same diameter (D) but different core lengths (L) to achieve the required outputs. In this case, the finished designs of machines must be produced in groups, where all the designs within a group are interdependent.

It takes many iterations to arrive at an optimal solution. The iterations require changes of values of variable for cost as well as performance constraints are achieved.

Thus, at last, it can be stated that the design of electrical machines is an iterative process wherein the assumed data may have to be varied many a times to arrive a desired design. Thus, due to above factors and circumstances, wide spread use of digital computers for design of electrical machines.

Advantages of Computer Aided Machine design: The digital computer has completely revolutionized the field of design of electrical machines. The computer aided design eliminates the tedious and time consuming hand calculations. The use of computer makes possible more trial designs. Thus, the advantages of use of a digital computer for the design of electrical machines may be as under:-

1. It has capabilities to store amount of data, count integers, round off results down to integers and refer to tables, graphs and other data in advance.

2. It makes it possible to select an optimized design with a reduction in cost and improvement in performance.

3. A large number of loops can be incorporated in the design programme and thus, makes it easier to compare different designs and best one can be selected.

4. It performs all simple arithmetic operations at a high speed and makes it possible to produce a design at a shorter time.

5. It is capable of automatic operation f design programme.

6. It reduces the probability of errors with highly accurate and reliable results.

7. Larger manufacturing savings can be obtained by optimization of design by use of computers.

8. It is capable of taking logical decisions by itself.

The high rate of performing calculations at reasonable cost and the ability to carry out logical decisions are the most important qualities of the present digital computers. Thus, the digital computers have been responsible for "complete revolution" in the field of electrical machine design.

Names of software for computer aided design: The following are the software used in the field of electrical machine design based on computer-aided technique:

1. FORTRAN language.

2. C language

3. CAD software

Optimization: The aim of optimization in the design of electrical machines is to choose the best solution for a given problem from the multitude of possible solutions.

The optimization process, involves the choice of various variables in such a manner that the design in regard to a particular feature is the best, and the same time, satisfies the limitations imposed on its performance. Hence, the optimization is the collective process of finding a set of conditions required to achieve the best results from a given situation.

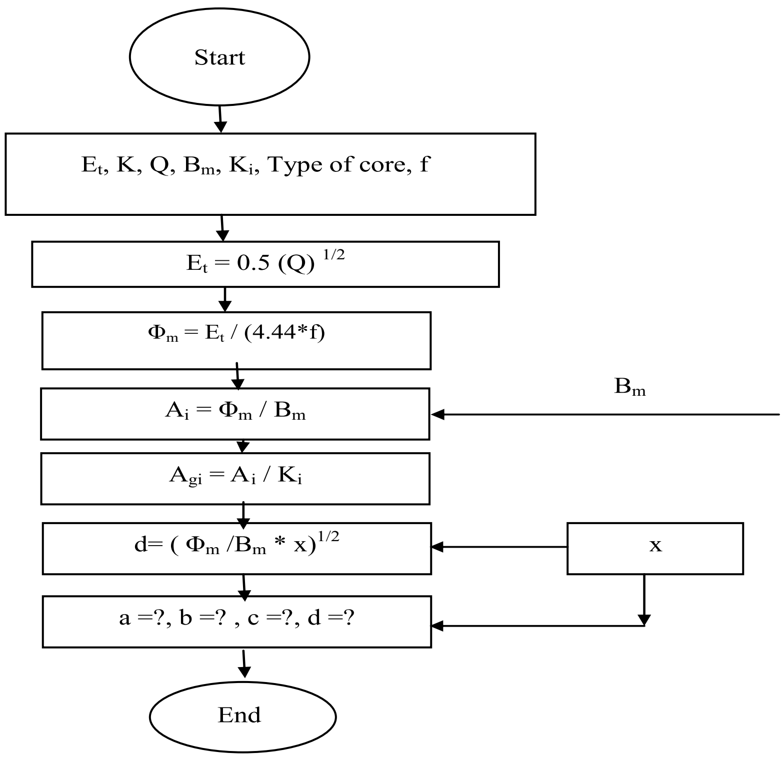
A characteristic feature of optimization in design of electrical machines is the presence of conflicting or opposing influences, for examples, the cost of the active materials, high temperature rise, poor power factor and thus unsatisfactory performance. Thus, the best design will be obtained by compromise of two main factors i.e. the cost and the performance of the machine

Q. 8: With the help of flow chart explain the computer based core and window dimension design of transformer.

Sol:

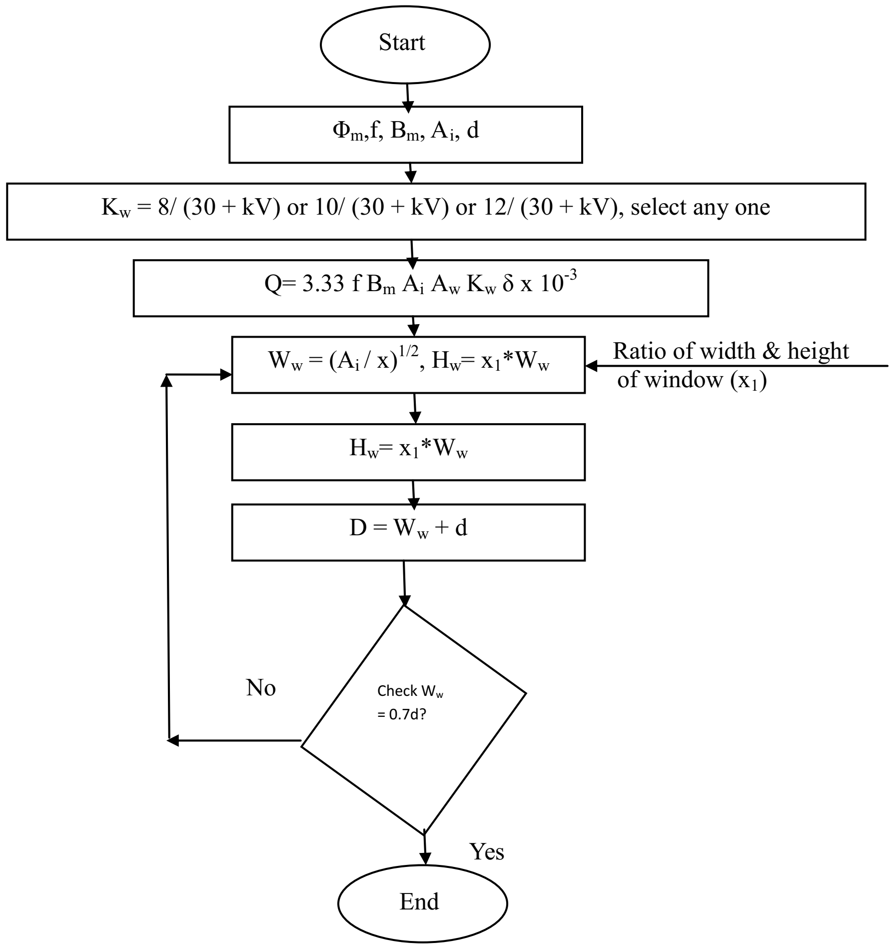
Flow charts for Transformer design:

Core design:



“x” indicates corresponding values of selected type of core.

Window dimensions Design:



Space factor (Kw) is large for larger output and smaller for small output.

For 700-1000kVA, $Kw = 12/(30 + kV)$

For 200-700kVA, $Kw = 10/(30 + kV)$

For about 1-200kVA, $Kw = 8/(30 + kV)$

Electrical Machine Design

TUTORIAL SHEET - 1

Q. 1: Mention three basic principles on which all the electrical machines are based.

Q. 2: List the important specifications as per ISI of (a) Transformer, (b) DC machines, (c) induction motor and (d) Synchronous machine.

Q. 3: A 15000kVA, 33/6.6kV, 3-phase, star-delta, core type transformer has the following data:

Net iron core of each limb = 1.5 x 10^{-3} m^2, net area of yoke = 1.8 x 10^{-3} m^2, mean length of flux path in each limb = 2.3m, mean length of flux path in each yoke = 1.6, number of turns in h.v. winding = 450.

Calculate the no-load current. Use the data as given below for mmf per metre and losses per kg

B_m Wb/m^2	0.9	1.0	1.2	1.3	1.4
Mmf A/m	130	200	420	660	1300
Iron loss W/ kg	0.8	1.3	1.9	2.4	2.9

Q. 4: A 4-pole, 25 H.P. 500V, 600r.p.m. series crane motor has an efficiency of 85%. The pole faces are square and the ratio of pole pitch is 0.67. Assuming an average flux density of 0.65 Wb/m^2 and ampere conductors per metre as 17000. Obtain the main dimensions of the core and particulars of suitable armature winding.

Q. 5: Differentiate between:

I) Power and Distribution Transformer

ii) Dry type and Oil immersed Transformer

Q. 6: Explain how output and losses of Transformer vary with dimensions of Transformer.

Q. 7: Explain different methods of cooling of transformers.

Q. 8: Explain the designing of core of transformer.

Q. 9: Explain the designing of transformer with cooling tubes.

Q. 10: Determine the dimensions for core and yoke for a 5kVA, 50Hz, single phase transformer. A rectangular core is used with long side twice as long as short side. The window height is 3 times the width of window. Voltage per turn is 1.8V, space factor = 0.2, current density = 1.8A/mm^2, flux density = 1Wb/m^2.

Electrical Machine Design

TUTORIAL SHEET - 2

Q. 1: Determine the suitable stator dimensions for a 500kVA, 50Hz, 3-phase alternator to run at 375r.p.m. Take mean flux density over the pole pitch as 0.55Wb/mm^2. The specific electric loading is 25,000A/m. The peripheral speed should not be exceed 35m/sec.

Q. 2: Determine for 250kVA, 1100V, 12 poles, 50Hz, 3-phase alternator **(i)** air gap diameter **(ii)** core length **(iii)** no. of stator conductors, **(iv)** no. of stator slots **(v)** cross section of stator conductors, assuming average air gap density as 0.6Wb/m^2.

Q. 3: A 3-phase alternator has a stator bore of 1.70m and core length of 0.35m. The average air gap density is approximate 0.55Wb/m^2. Determine a suitable no. of slots and conductors per slot for a terminal voltage of 6600V, 50Hz & 375r.p.m. Use star connection

Q. 4: Obtain the main dimensions of the rotor of a 50MVA, 2 poles, 50Hz synchronous generator. The peripheral speed is smitted to approximately 160m/sec. Take an electric loading of 65,000A/m and a mean air gap density of 0.575Wb/m^2. Assume a gap length of 25mm.

Q. 5: A 2-pole, 50Hz, turbo-alternator has a core length of 1.5m, the mean flux density over the pole pitch is 0.5Wb/m^2. The stator ampere conductors are 25,000 and the peripheral speed is 100m/sec. The average span of coils is one pole pitch. Determine the output which can be obtained from the machine.

Q. 6: Explain why a water wheel generator is a slow speed machine, whereas a turbo-generator is a high speed machine.

Q. 7: Give the effect of SCR on machine performance.

Q. 8: Give the factor considered for the selection of armature slots.

Q. 9: Explain the runaway speed as used in synchronous machine.

Q. 10: Find the dimensions of 100MVA, 11kV, 50Hz, 150r.p.m., 3-phase water wheel generator. The average air gap density is 0.65Wb/m^2 and the ampere conductors per metre are 40,000. The peripheral speed should not exceed 65m/sec at normal running speed in order to limit the runaway peripheral speed.

Electrical Machine Design

TUTORIAL SHEET - 3

Q. 1: Derive the output equation of D.C. machine.

Q. 2: Discuss factors deciding no. of poles. Give advantages and disadvantages of using large no. of poles.

Q. 3: Discuss the effect of slot reluctance of air gap.

Q. 4: Explain the tentative deign of field winding.

Q. 5: A 4-pole, 25 H.P. 500V, 600r.p.m. series crane motor has an efficiency of 85%. The pole faces are square and the ratio of pole pitch is 0.67. Assuming an average flux density of 0.65 Wb/m^2 and ampere conductors per metre as 17000. Obtain the main dimensions of the core and particulars of suitable armature winding.

Q. 6: Calculate the diameter and length of armature for a 7.5kW, 4 pole, 1000r.p.m., 220V shunt motor. Given: full load = 63%, maximum gap density = $0.9Wb/m^2$, specific electric loading = 30,000 conductor/metre, field current is 2.5% of the rated current. The pole faces are square.

Q. 7: Find the dimensions of a 2000kW, 250V, 6-pole, 1000r.p.m. generator. The maximum value of flux density is $0.87Wb/m^2$ and ampere conductors per metre of armature periphery are 31,000. The ratio of pole arc to pole pitch is 0.67 and efficiency is of 91%. Assume the ratio of length of core to pole pitch is 0.75.

Q. 8: What are the various considerations for selection of proper value of commutator diameter.

Q. 9: A 350kW, 500V generator has 8 poles, an armature diameter of 1.3m and core length of 0.35m. a duplex wave winding is accommodated in 114 slots with 6 coil sides per slot. The axial length of commutating poles is 0.2m and the gap length under the commutating poles is 10mm. Find the necessary mmf for each interpole if the specific permeance is 60×10^{-6}. Find also the number of turns.

Q. 10: The following are the limiting parameters for a conventional industrial machine:

average flux density in air gap = $0.8Wb/m^2$

peripheral speed of the machine = 40m/sec.

average emf between adjacent segments = 20V

minimum pitch of commutator segments = 4mm.

The frequency of flux reversal in the armature should not be less than 40Hz on account of economic considerations. Calculate the maximum values of armature voltage that can be developed in a machine.

Electrical Machine Design

TUTORIAL SHEET - 4

Q. 1: Why hydrogen cooling is preferred over air cooling.

Q. 2: Explain direct cooling. Give merits and demerits of it.

Q. 3: Explain short time rating of machine. Give output of a machine with give dimensions in longer with short time rating than that of a machine with the continuous rating.

Q. 4: List and explain the limitations being imposed on the design of a machine.

Q. 5: Define "magnetic materials". Explain how paramagnetic and diamagnetic materials differ from ferro-magnetic materials. Give the names of magnetic materials used in the manufacture of electrical machines with their special characteristics.

Q. 6: A 5kW motor can be considered to be a homogeneous body weighing 200kg and having a specific heat of 0.09cal/g/^{0}C. Cooling surface area of the motor is 0.25m^2, its emissivity is 30Watts/m^2/^{0}C and its full load efficiency is 90%. For an ambient temperature of 25^{0}C, estimate the temperature of the body after 2 hours of continuous full load operation and **(ii)** final temperature of the motor.

Q. 7: The losses of a 60MW hydrogen cooled alternator at full load amount to 750kW,. The volume of hydrogen out from the alternator after cooling of the machine is 10m^3/sec. at 2000mm of mercury gauge pressure above the atmospheric pressure of 760mm. The temperature of hydrogen leaving the coolers is 25^{0}C. Determine the temperature rise of hydrogen assuming specific heat of hydrogen at constant pressure of 1240 J/kg-^{0}C and weight of 11.2m^3 of hydrogen at 0^{0}C and 760mm of mercury to be 1kg.

Q. 8: In a closed air circuit for cooling a 60MW alternator having an efficiency of 97%, 85 percent of the losses are carried away by the cooling air. Calculate the weight of air required in Kg per minute for a temperature rise of 30^{0}C when the alternator is at full load. The specific heat of air at constant pressure is 1000J/kg-^{0}C.

Q. 9: Explain what are the insulating materials? What are the electrical properties of the insulating materials and on what factors, these properties depends?

Q. 10: A heat radiating body can be assumed to be spherical surface with coefficient of emissivity = 0.8. The temperature of body is 60^{0}C and that of walls of room in which it is placed, is 20^{0}C. Find the heat radiated from the body in Watt /m^2.

Electrical Machine Design

TUTORIAL SHEET - 5

Q. 1: What are different approaches of computer aided design for optimization.

Q. 2: What is mean by performance prediction design in computer aided design.

Q. 3: Discuss the merits of computer aided design in comparison of conventional design.

Q. 4: Explain the term "Optimization".

Q. 5: With the help of flow chart explain the computer based core and window dimension design of transformer.

Q. 6: Discuss the analysis and synthesis methods for machine design.

Q. 7: Develop the flow chart for the core and window dimension design of a transformer.

Q. 8: With the help of flow chart, discuss the computer based design of main dimensions and stator design of induction motor.

Q. 9: Discuss the computer based design technique for main dimensions and armature core and armature winding in case of D.C. Machine.

Q. 10: Discuss the design procedure for developing the synchronous machine.

Computer Applications of Electrical Machine Design

1.1. INTRODUCTION

Computer Aided Design for machines (Role of Computers for Machine Design) The design of electrical machine (including transformers) consist essential solutions of many complex and diverse engineering problems and these problems are interrelated to each other. Thus, the electrical machine design is a mathematical indeterminate problem with many solutions, as number of unknowns is greater than the no. of equations. But the machine design can be achieved by correct decisions based upon the judgement and intuition and very clear understanding of the project. In today's world, the prime endeavour of an electrical machine lies in designing the machine suited to the work place, such as:

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The manual design procedure of a machine is very time consuming and tedious work, needs more man power and less accuracy. Further, during the manual design, lot of approximations are required to be considered which gives inaccurate results. Thus, we can use a so-called computer language to solve the above mentioned problems and thus this approach is called as **Computer aided electrical machine design**.

The process of design of a single electrical machine may be divided into three major design problems:

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It takes many iterations to arrive at an optimal solution. The iterations require changes of values of variable for cost as well as performance constraints are achieved.

Thus, at last, it can be stated that the design of electrical machines is an iterative process wherein the assumed data may have to be varied many a times to arrive a desired design. Thus, due to above factors and circumstances, wide spread use of digital computers for design of electrical machines.

1.2 ADVANTAGES OF COMPUTER AIDED MACHINE DESIGN The digital computer has completely revolutionized the field of design of electrical machines. The computer aided design eliminates the tedious and time consuming hand calculations. The use of computer makes possible more trial designs. Thus, the advantages of use of a digital computer for the design of electrical machines may be as under:-

1. It has capabilities to store amount of data, count integers, round off results down to integers and refer to tables, graphs and other data in advance.

2. It makes it possible to select an optimized design with a reduction in cost and improvement in performance.

3. A large number of loops can be incorporated in the design programme and thus, makes it easier to compare different designs and best one can be selected.

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7. Larger manufacturing savings can be obtained by optimization of design by use of computers.

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The high rate of performing calculations at reasonable cost and the ability to carry out logical decisions are the most important qualities of the present digital computers. Thus, the digital computers have been responsible for "complete revolution" in the field of electrical machine design.

1.2.1 Names of software for computer aided design The following are the software used in the field of electrical machine design based on computer-aided technique:

1. FORTRAN language.

2. C language

3. CAD software

4. MATLAB software

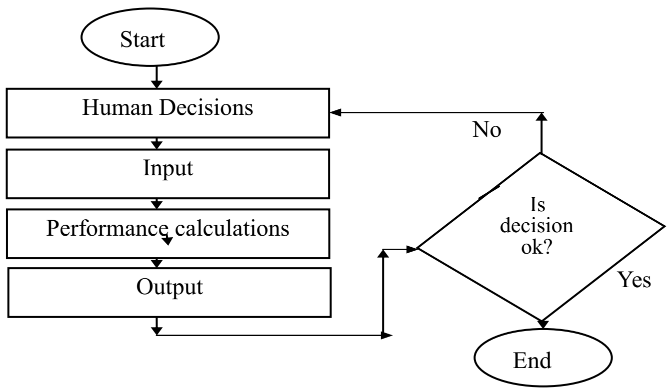
1.3 COMPUTER AIDED DESIGN - DIFFERENT OPTIMIZATION APPROACHES The application of digital computers to the problem of electrical machine design was first introduced in 1950. In the early stage, this was limited to design of transformers. In the year 1956, the applications of digital computers are discussed to the design of transformers as well as rotating machines. In the same year, Veinatt published a research of application of digital computers for the design of induction motors. A flow chart was developed giving basic procedure for the design of polyphase induction motor. This paper in fact developed the analysis method for the design of polyphase induction motor.

The concept of optimization in electrical machine design was introduced by Godwin in 1959 and a program was developed for design of squirrel cage induction motors. In 1959, Heroz introduces the concept of two commonly acceptable approaches to machine design, namely:

i) Analysis method and ii) Synthesis method.

1.3.1 Analysis Method The analysis method of design is depicted as in fig. In this method, the choice of dimensions, materials and type of construction are made by the designer and these are presented as input data to the computer. The performance was calculated by the computer and is returned to the designer for examination. The designer examines the performance and makes choice of input, if necessary and performance is recalculated. This procedure is repeated till the performance requirements are satisfied.

The use of term "analysis method" means the use of computer for the purpose of analysis leaving all exercises of judgement to the designer.



The advantages of analysis method are:-

1) Easy to program, to use and to understand.

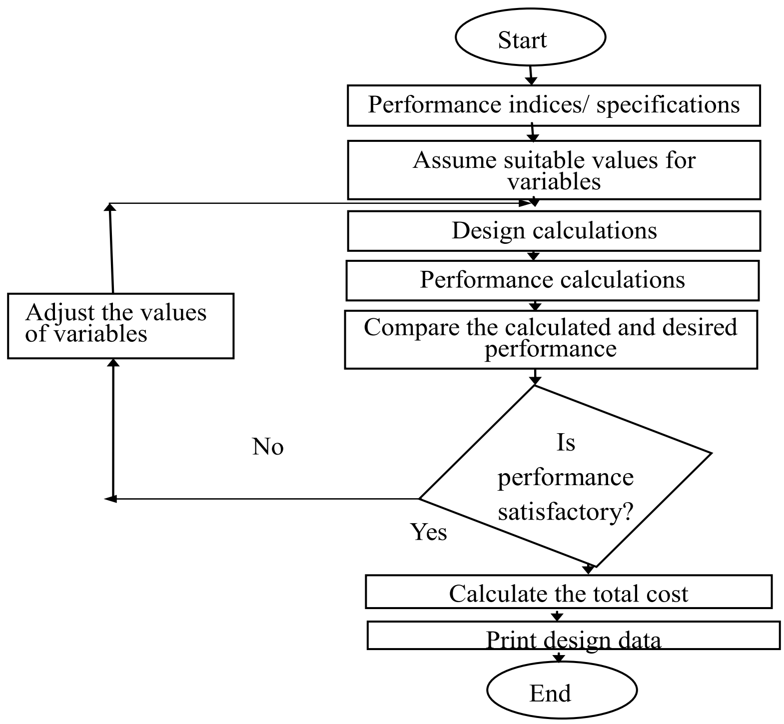
2) It results in time saving thereby giving quick returns on investments.

3) Programs are simple.

4) Highly acceptable results of analysis method by the designers.

1.3.1 Synthesis Method The synthesis method is as depicted in fig. The desired performance is given as input to the computer. The logical decisions required to modify the values of variables to arrive at the desired performance are incorporated in the program at the set the instructions. The synthesis method of design implies designing a machine which satisfies a set of specifications or performance indices. Given a set of performance to satisfy them. So the synthesis design should be such that it produces an optimum design using optimization.

The greatest advantage of synthesis method is as the saving in time in lapsed time and in engineering man hours on account of the decision left to the computer itself.



The synthesis method suffers with a number of serious disadvantages such as:-

1) This method involves too much logic since the logical decisions are left to the computer to take. Now, these logical decisions have to incorporated in the program and before, incorporation, the team of design engineers are to agree upon them.

2) The logical decisions to arrive at a optimum design are too many and then, there are too many people with too

many ways to suggest to produce the optimum design and thus, it becomes really hard to formulate a logic for obtaining an optimum design.

3) The formulation of a synthesis program taking into account of factors listed would make it too complex. So, cost of computer program becomes high and thus use of a large computer and also large running time involves huge expenditure.

4) The synthesis program formulated at a high cost cannot be used for ever, as due to changes in materials, manufacturing techniques, performance standards, relative cost of materials, market conditions etc., the program has to be changed and up dated keeping. Thus synthesis method requires additional efforts and cost in order for the above.

1.3.1 Hybrid Method This method incorporates both the analysis as well as synthesis methods in the program. Since the synthesis methods involve greater cost, the major part of the program is based upon the analysis with a limited portion of the program being based upon synthesis.

1.4 OPTIMIZATION The aim of optimization in the design of electrical machines is to choose the best solution for a given problem from the multitude of possible solutions.

The optimization process, involves the choice of various variables in such a manner that the design in regard to a particular feature is the best, and the same time, satisfies the limitations imposed on its performance. Hence, the optimization is the collective process of finding a set of conditions required to achieve the best results from a given situation.

A characteristic feature of optimization in design of electrical machines is the presence of conflicting or opposing influences, for examples, the cost of the active materials, high temperature rise, poor power factor and thus unsatisfactory performance. Thus, the best design will be obtained by compromise of two main factors i.e. the cost and the performance of the machine

1.4.1 General procedure of optimization The general objective of the optimization is to choose a set of values of the independent variables, subject to various restrictions, which will produce the desired response for the particular problem under examination. A general procedure of optimization is as under:-

1. Define a suitable objective for the problem under examination.

2. Examine the restrictions imposed upon the problem by external agencies.

3. Choose a system or systems for study.

4. Examine the structure of each system and the interrelationship of the system elements and streams.

5. Construct a model for the system. This is a technical design stage which allows the objective to be defined in terms of the system variables.

6. Examine and define the internal restrictions placed on the variables.

7. Carry out the simulation by expressing the objective in terms of the system variables, using the system model. This is the objective function.

8. Analyse the problem and reduce it to its essential features. This reduction is necessary in many cases to allow optimization to carry.

9. Verify that the proposed model represents the system being studied.

10. Determine the optimum solution for the system and discuss the nature of the optimum conditions.

11. Using the information thus obtained, repeat the procedure until a satisfactory result is obtained.

1.5 VARIABLES AND CONSTRAINTS The numerical quantities for which values are to be chosen in producing a design are called “design variables”. The objective function 'Y' is expressed in terms of the independent variables v, where v represents all the variables, $v_1, v_2, \ldots\ldots\ldots\ldots\ldots, v_n$ as,

$$Y(v) = Y(v_1, v_2, \ldots\ldots\ldots\ldots\ldots, v_n)$$

subject to in restrictions, generally termed as Constraints, of the form,

$$g_i(v) = 0$$

or $g_i(v) \leq 0$

Here, $g_i(v)$ can be variable or a function.

The sole considerations are mathematical and the optimization techniques are determined by the mathematical structures of the objective function and the associated restrictions.

1.6 COMPUTER AIDED DESIGN OF TRANSFORMER

1.6.1 Basic Aspects

The transformer is a static device which transfers the electrical energy from one or more primary windings to one or more secondary windings using the law of electro-magnetic induction using the magnetic circuit. Class of transformers (power or distribution), type of construction (core or shell type), kVA ratings, voltage level, type of connections, percentage of impedances and tappings, temperature rise are the basic requirements of customer's specifications.

To achieve the better performance, the whole design procedure is divided into several parts as follows:-

i) Core design

ii) Window dimension design

iii) Yoke design

iv) Overall design

v) Low voltage winding design

vi) High voltage winding design

vii) Resistance calculation.

viii) Leakage reactance calculation.

ix) Loss calculation.

x) Efficiency calculation.

xi) No-load current calculation.

1. Core design: Core design is dealt with the type of core (core or shell) of the transformer. The value of 'K' is constant depending upon the type of transformer (power or distribution). The allowable flux density in the core lies between 1.0 to 1.35Wb /m^2 for distribution transformer and between 1.25 to 1.45 Wb/m^2 for power transformers. The core section of the core type transformer can be

a. Square.

b. Cruciform or 2-stepped

c. 3-stepped

d. 4-stepped

2. Window dimensions: Flux density in the window section of the transformer is same as that of the core of the transformer. For large power transformers upto 50kVA self cooled, current density, δ, usually lies between 1.1 to 2.3 A/mm^2, for large power transformers self-oil cooled or air blast type, δ = 2.2 to 3.2 A/mm^2 and for large power transformers with forced circulation of oil or water cooled transformers, δ = 5.4 to 6.3 A/mm^2.

3. Yoke design: Area of the yoke is taken as 15 to 25 percent larger than that of the core of the transformer. The section of the yoke is either rectangle or square. For rectangular yoke, the yoke highest side of the laminated core (width of the largest stamping) is taken as depth core.

4. Low voltage winding design: For the selection of low voltage winding, either helical, cylindrical or cross over winding arrangements are preferred. Dimensions of the conductor of the low voltage winding is taken based on the area of the conductor.

5. High voltage winding design: Design of high voltage winding is similar to the low voltage winding design. Higher percentage of tapping increase the flexibility of transformer. Thus, helical or cross over winding arrangements are preferred in this case and dimensions of the conductor of the low voltage winding is taken based on the area of the conductor.

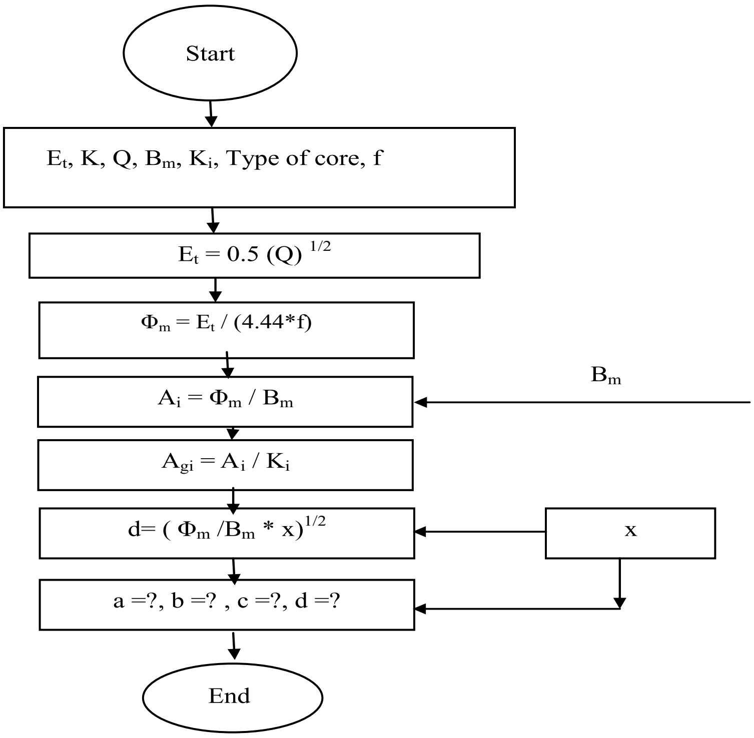
1.6.2 List of Symbols used

Bm = maximum flux density	Q = Transformer rating in kVA
f = frequency in Hz	Et = emf per turn
Ai = area of iron core	d = diameter of circumscribing circle
a1, b1 = sides of core	D = distance between two core limb
Ep = 1^0 side voltage (phase) HV	Es = 2^0 side voltage (phase) (LV)
δ1 = current density	Aw, Ww, Hw = area, width & height of window
Ay = area of yoke	Agi = gross area of iron core
Hy = height of yoke	Dy = depth of yoke = width of largest stamping, a
H = height of frame	W = width of frame
Tp = no. of turns on 1^0 side	Ts = no. of turns on 2^0 side
Tl = turns per layer	Vm = maximum voltage between layers
Is = 2^0 phase current	As = area of 2^0 conductor
Lcs = axial length of LV winding	Cls = clearance between core and LV winding
bs = radial depth of LV winding	Dli = inside diameter of LV winding
V1p = phase voltage = Vp (delta)	Tc = turns per coil
Ip = 1^0 phase current	Ap = area of conductor in hv side
dc= diameter of bare conductor	dg = gross diameter of conductor with insulation
Tl = turns per layer	Lcp = axial length of HV winding
Clp = clearance between core and Hv wdg.	bp = radial depth of HV winding
Lmp / Lms = length of mean turn of HV/ LV windings	Dmp / Dms = mean diameter of HV/ LV windings
ρ = resistivity	Rp /Rs = resistance of the HV/ LV winding
RRp = resistance referred to HV wdg.	Rpu = p.u. resistance
Lmt = length of mean turn	Lc = axial length of the winding
Xp = leake reactance referred to 1^0 wdg.	Xpu = p.u. reactance
Zpu = p.u. impedance	reg. = regulation
Cu loss = copper losses	STR = stray load losses
Voli = volume of iron	weight = weight of iron core
Corel = core losses	Voy = volume of yoke
Weighty = weight of yoke	Corely = core losses in yoke
Tcloss = total core losses	Eff = efficiency
Atc = mmf in core per metre	Tatc = total mmf in core
Aty = mmf in yoke per metre length	Taty = total mmf in yoke section
Tmmf = total mmf in yoke and core	ATo = mmf per phase
Im = magnetizing current	Il = loss component of no load current
Io = no load current	

1.6.3 Flow charts for Transformer design:

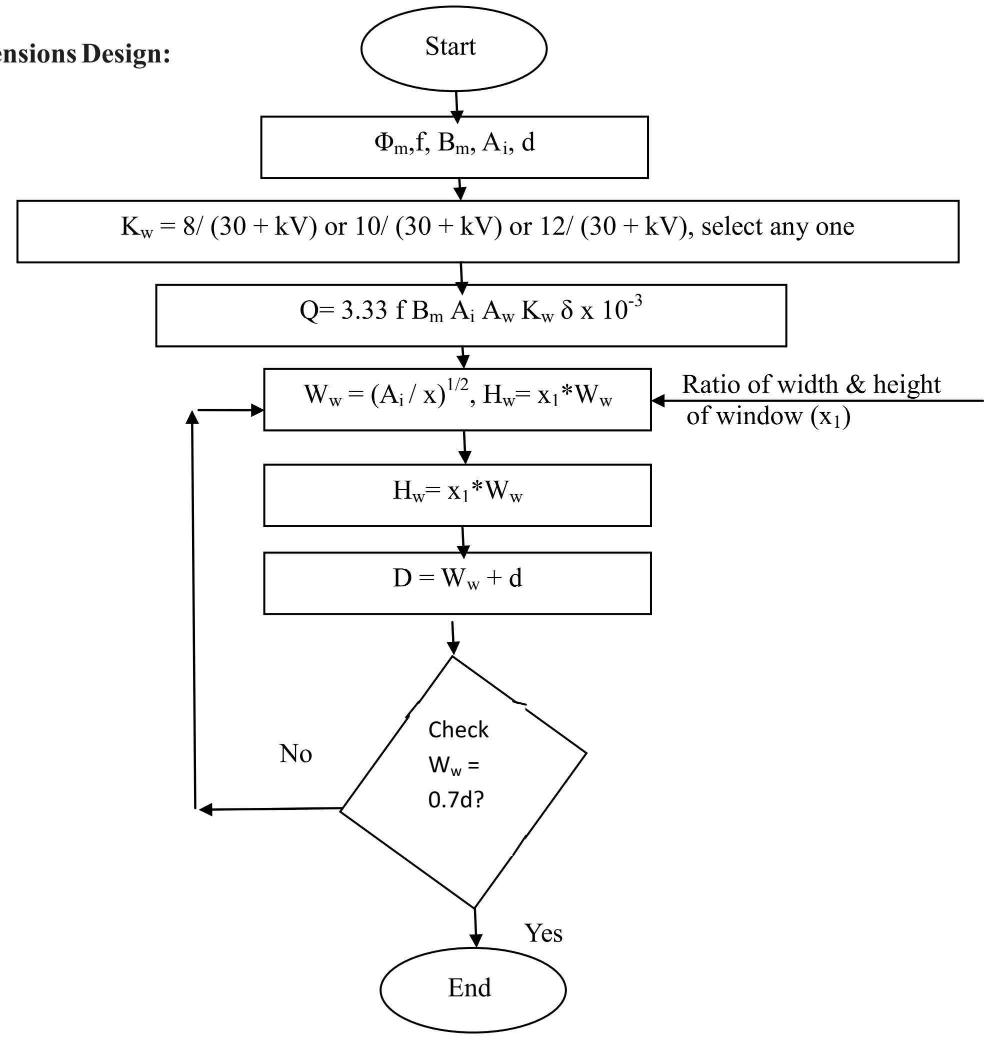
Flow charts for Transformer design:

Core design:

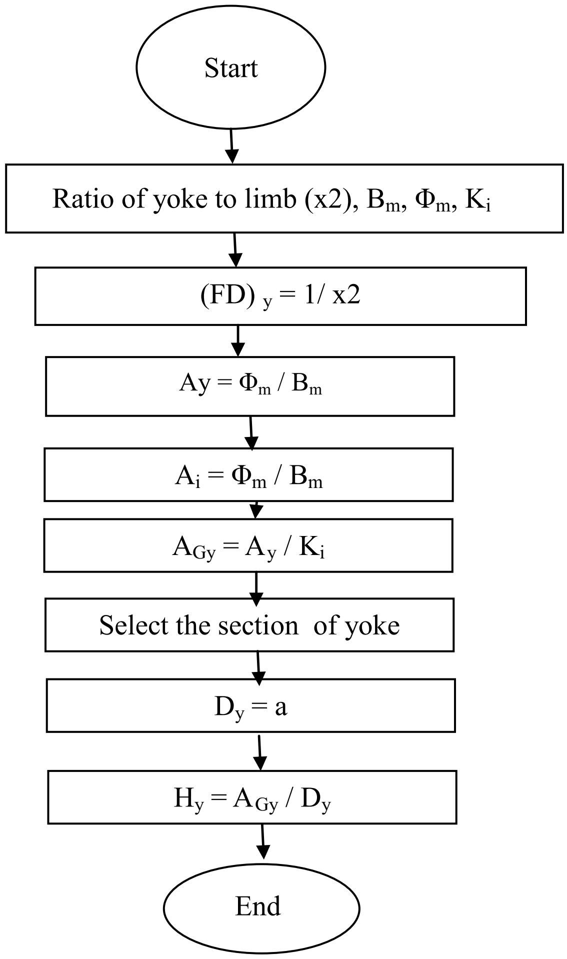


"x" indicates corresponding values of selected type of core.

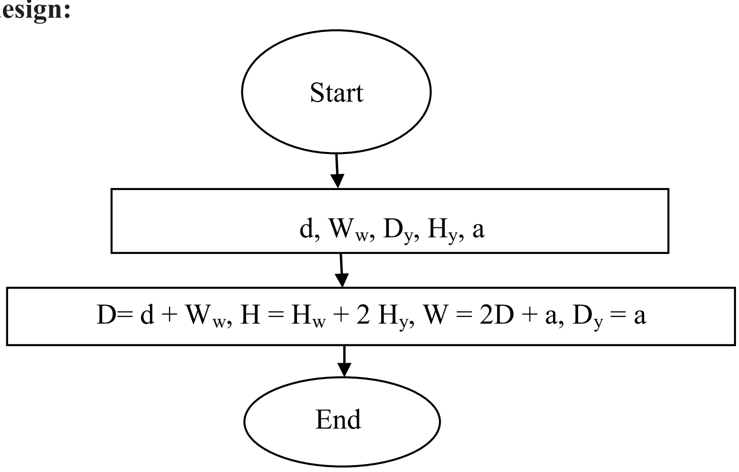
Window dimensions Design:



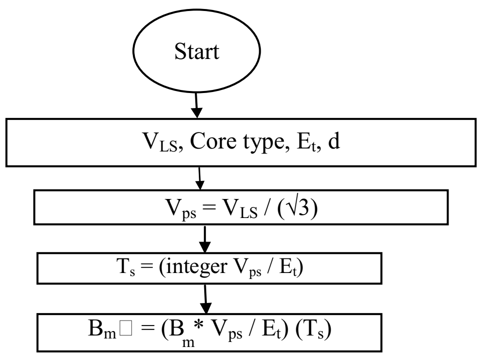
Yoke design:

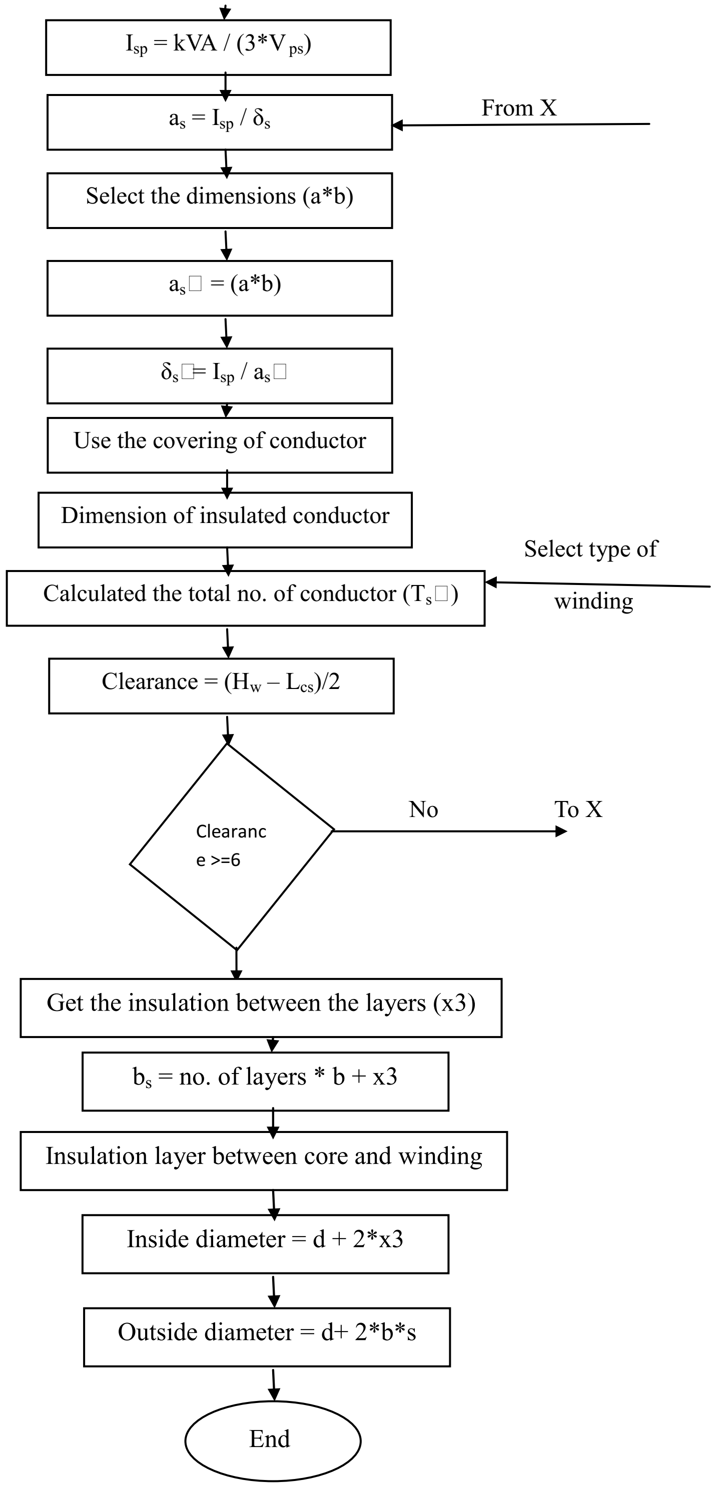


Overall dimensions design:

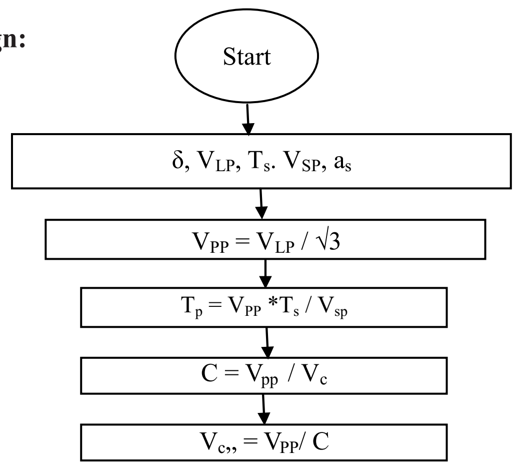


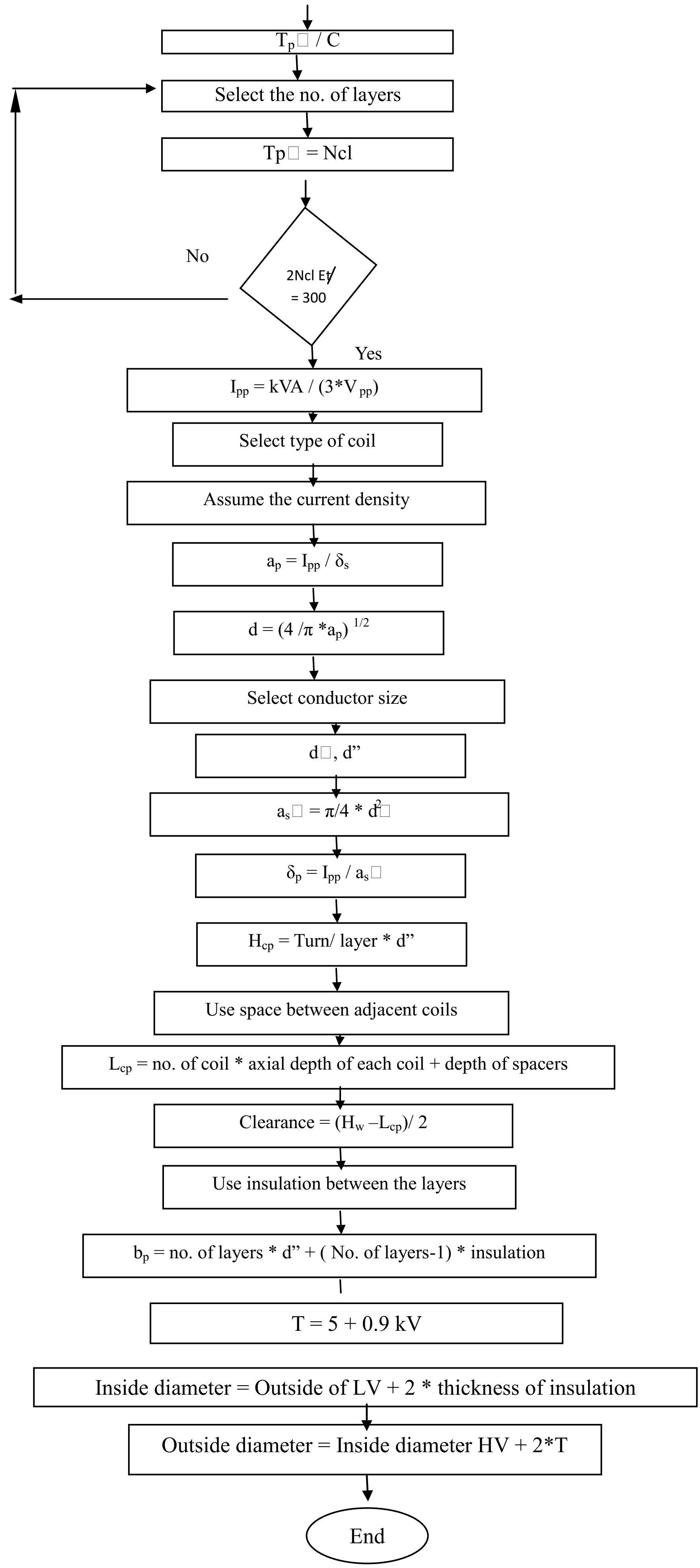
L.V. Winding design:



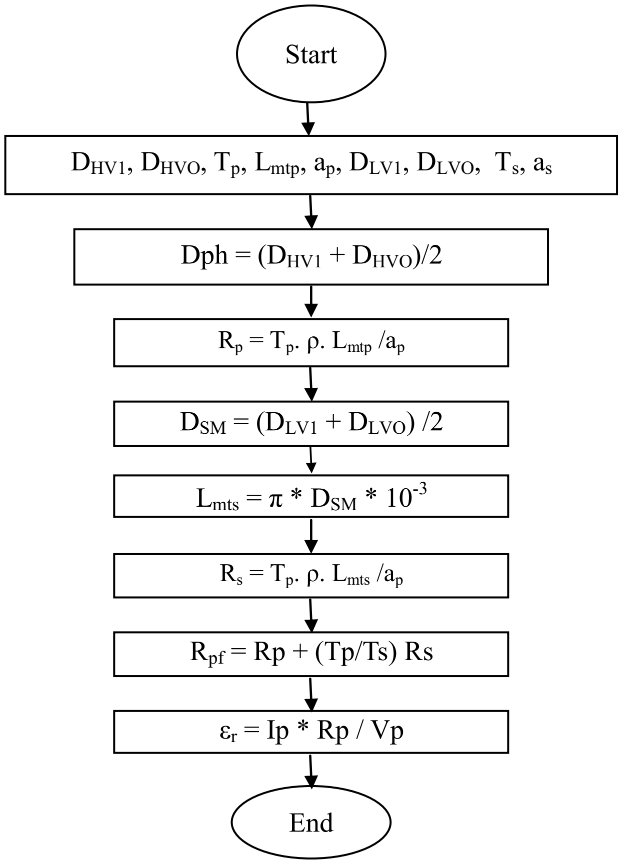


H.V. Winding design:

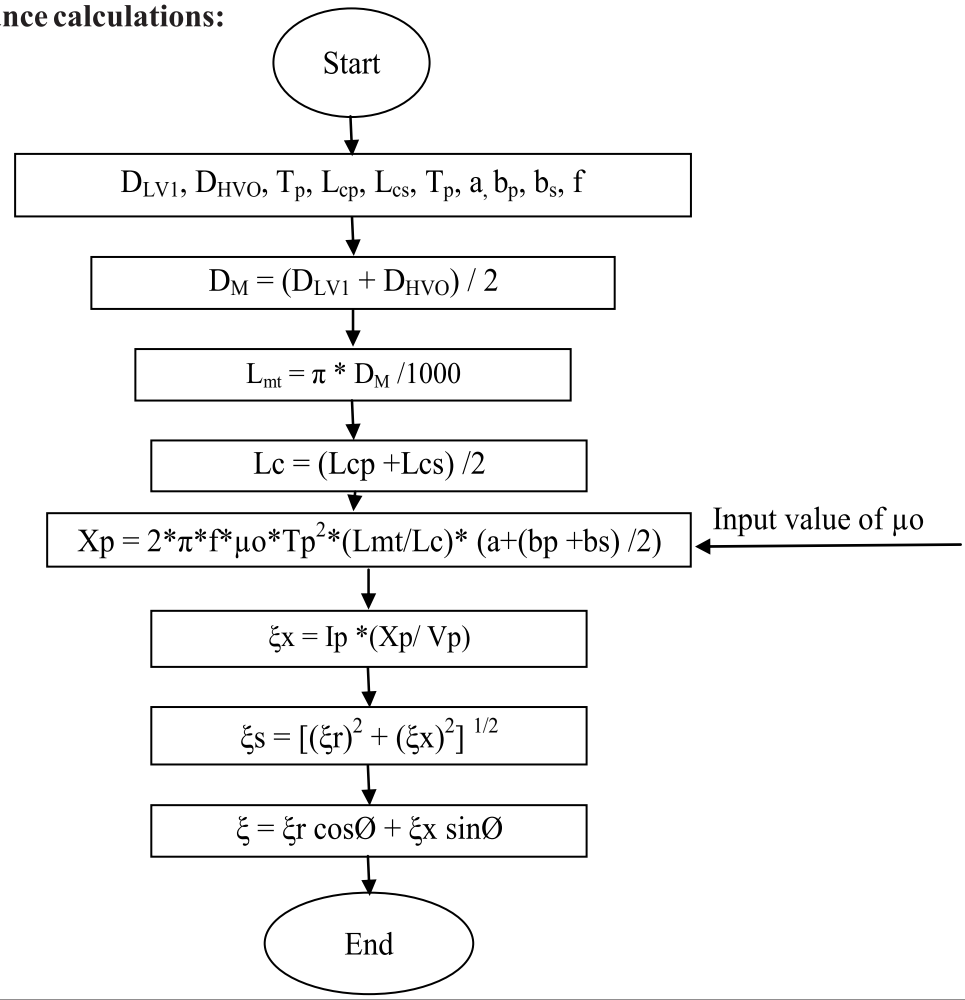



Tp□ / C
Select the no. of layers
Tp□ = Ncl
No
2Ncl Et/ = 300
Yes
Ipp = kVA / (3*V pp)
Select type of coil
Assume the current density
ap = Ipp / δs
d = (4 /π *ap) 1/2
Select conductor size
d□, d”
as□ = π/4 * d2□
δp = Ipp / as□
Hcp = Turn/ layer * d”
Use space between adjacent coils
Lcp = no. of coil * axial depth of each coil + depth of spacers
Clearance = (Hw –Lcp)/ 2
Use insulation between the layers
bp = no. of layers * d” + (No. of layers-1) * insulation
T = 5 + 0.9 kV
Inside diameter = Outside of LV + 2 * thickness of insulation
Outside diameter = Inside diameter HV + 2*T
End

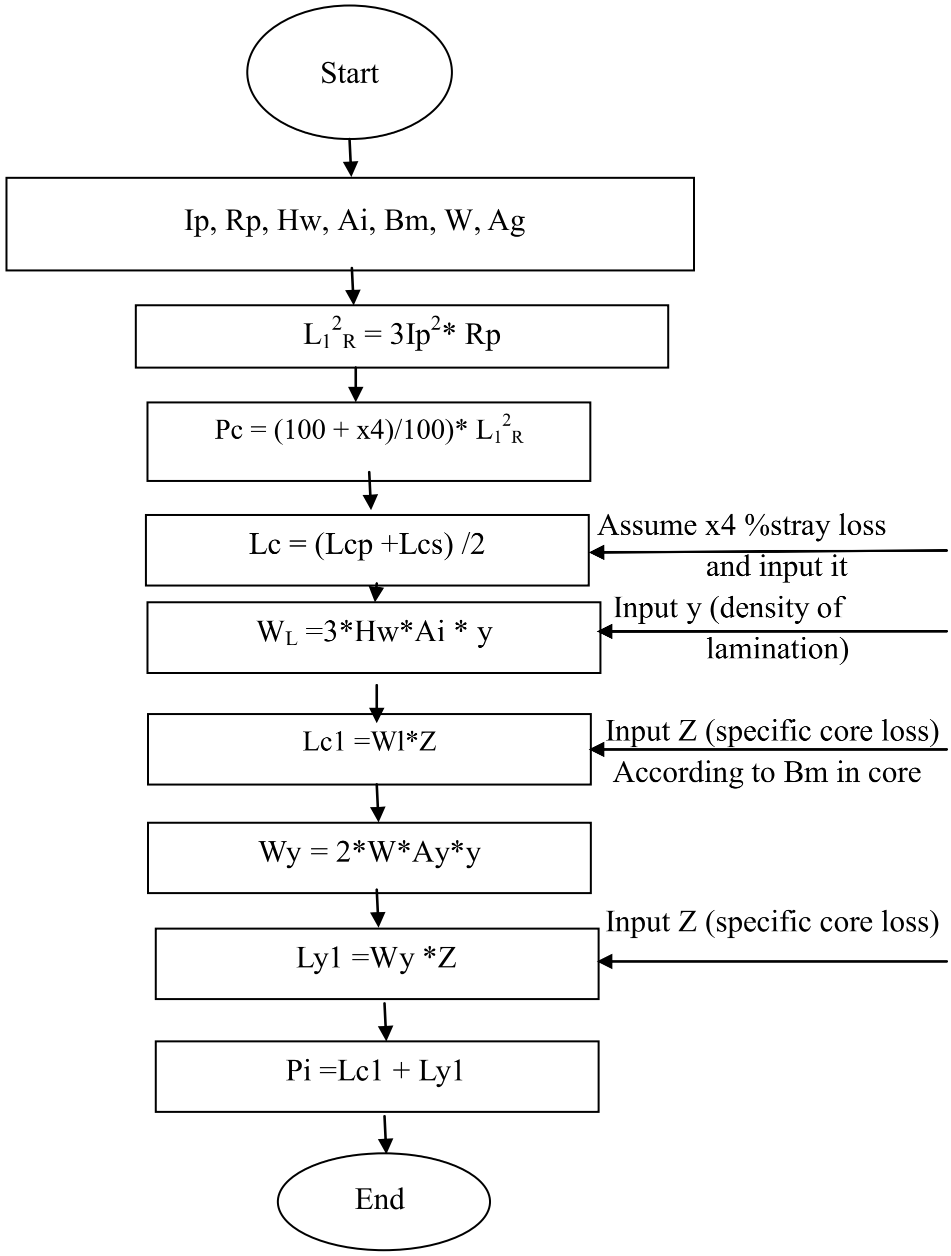
Resistance calculations:



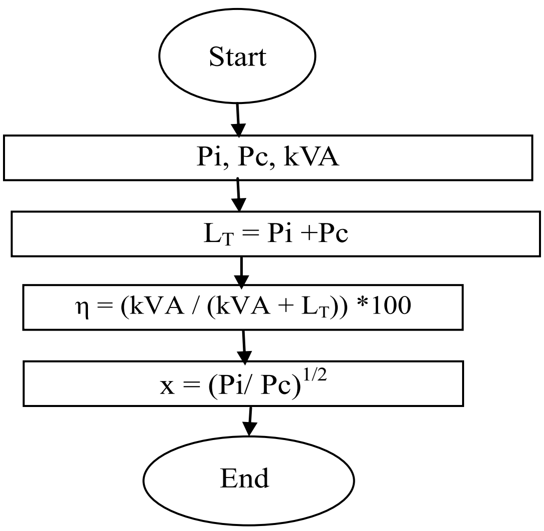
Leakage reactance calculations:



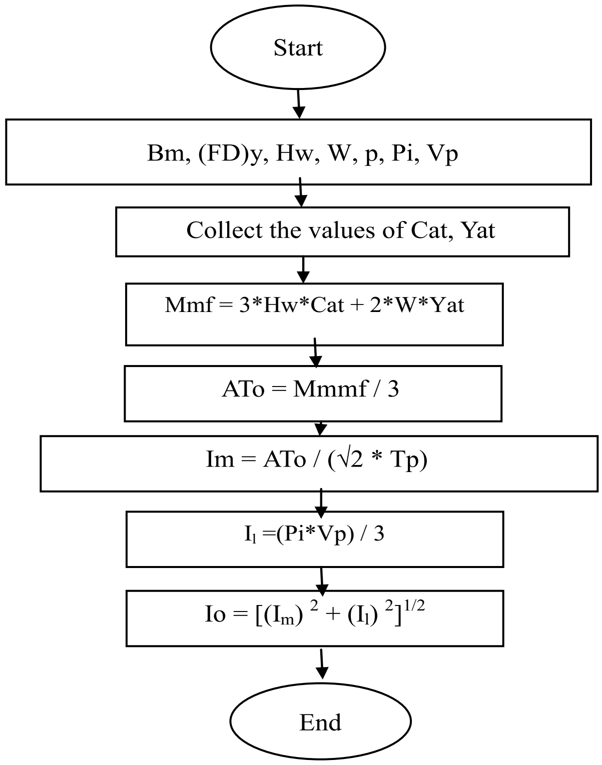
Loss calculations:



Efficiency calculations:



No load Current calculations:



Cat = value of ampere conductors per turn turns to the value of flux density in core

Yat = value of ampere conductors per turn turns to the value of flux density in yoke

1.7 COMPUTER AIDED DESIGN OF INDUCTION MOTORS

1.7.1 Basic Aspects

The design features of an induction motor are:

1. **Constructional features**
   - **a)** Main dimensions
   - **b)** Stator design
   - **c)** Rotor design

2. **Performance calculation**
   - a) No load current
   - b) Loss component
   - c) Leakage reactance
   - d) Losses and efficiency

1. **Main dimensions**: Main dimensions includes the dimensions of stator core i.e. length (L) and diameter (D) of the stator core. To calculate these two parameters it is to assume some parameters like magnetic loading (Bav = 0.45Wb/m^2), electric loading (ac = 45000A/m), efficiency (0.8 to 0.93) and power factor (0.8 to 0.9). The ratio of L / τ is taken into the account to fulfil the any one of following objectives: **Design features L / τ**Minimum cost 1.5 to 2Good power factor 1.0 to 1.25Good efficiency 1.5Good overall design 1.0

When the values of D and L are available, then it is to select the number of ventilating ducts. To get proper core length, the term stacking factor (Ks) is taken into the account (the average value is 0.9)

2. **Stator design**: The stator design deals with the static part of the motor whose elements are slot, conductors and

coils. The low voltage motors are always connected in delta connection whereas the high voltage motors are connected in star connection. So, it is calculate the no. of stator turns per phase (Ts). To limit the leakage reactance, the no. of stator slots per pole per phase should never be less than 2. For open slots on stator, the slot pitch should be between 15 to 25mm whereas for semi-closed slots, the slot pitch should be less than 15mm. Another important factor is no. of stator conductors per slot (Zss). If Zss is not proper, Bav is to be modified and thus new dimensions of the machine is required to be develop. The current density in the stator winding is usually taken between 3-5A/mm^2. For selection of bare and insulated diameters of the conductors, proper choice is required. For motor upto the rating of 50kW, round copper wires are used for stator winding, whereas for machine rating more than 50kW, rectangular copper conductors are preferred. The flux density in the 1/3 height of stator teeth lies between 1Wb/m^2 to 1.7Wb/m^2. Flux density in the core is higher than the flux density in the teeth of stator.

3. **Rotor design**: Current density in the rotor bar lies between 4-7A/mm^2. To make smooth air gap and smaller in size, higher value of current density is preferred.

4. **No load current**:

a) Magnetizing Current

Magnetizing component of no load current should be low. Magnetizing current can be calculated from the respective B-H curve according to selection of different materials for stator core, stator teeth, rotor core, rotor teeth, gap contraction factor and Carter's coefficient. Total value of mmf is equal to mmf in the air gap at 60^0 from the inter polar axis + mmf at 1/3 height of the air gap + mmf of stator core + mmf at 1/3 height of rotor teeth + mmf at rotor bar

b) Loss component of no-load current

Iron losses, friction and windage losses are taken into the consideration. Stator teeth and stator core are most effective part to produce the iron losses. Friction and windage losses lies between 0-2.5% of the output of the machine. **Leakage reactance**: It is required to produce a maximum useful flux and a very little leakage flux. Thus it is required to make a low reluctance path. This flux, which strays away, completes its circuit by paths, which prevents its utilization in the functioning of the machine. There are different types of slots, size and shape of slot are so selected to make the minimum leakage flux.

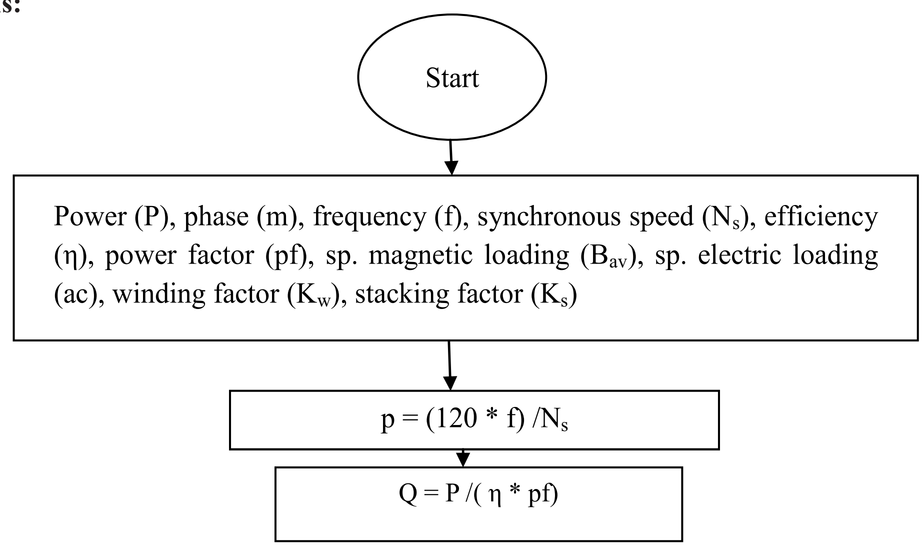
1.7.2 List of Symbols used

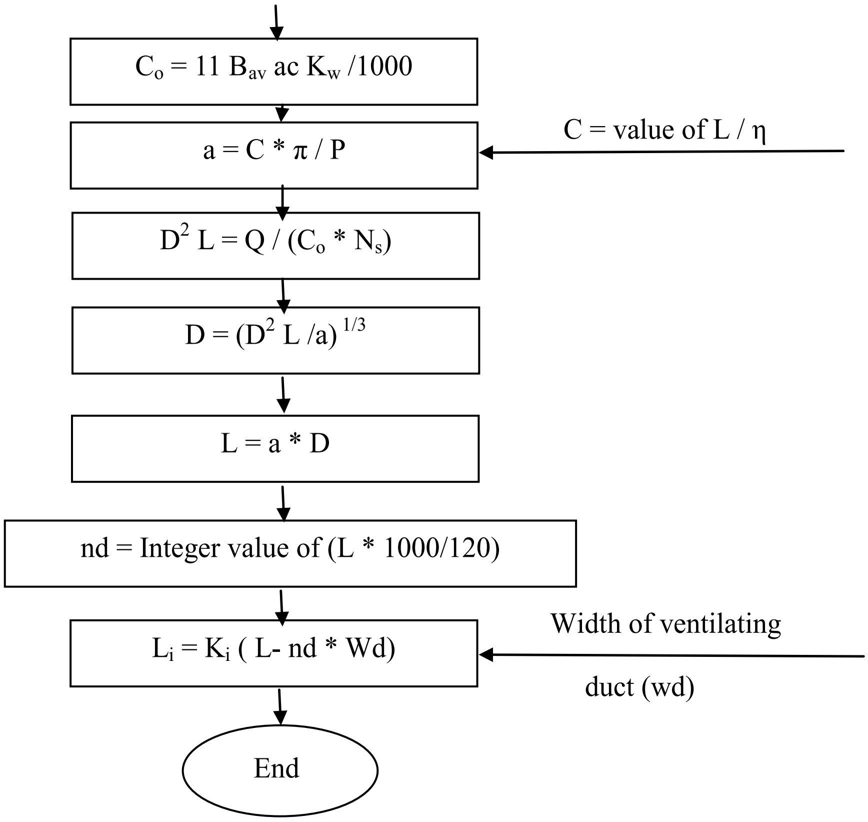
Po = power output in kW	Q = kVA input
f = frequency in Hz	P = no. of poles
ns = synchronous speed, in r.p.sec.	Co = output coefficient
D = diameter	L = length of machine
Bav = specific magnetic loading Wb/m^2	ac = specific electric loading
Kw = winding factor	Li = Net iron length
eta = efficiency of the machine	pf = power factor
Es = stator voltage per phase	Φm = flux per pole
Ts = stator turns per phase	qs = no. of stator slots per pole per phase
Ss = stator slots	Yss = stator slot pitch
Zs = stator conductors	Zss = stator conductors per slot
Nc = no. of stator coils	Cs =coil span
Kp = pitch factot	Kd = distribution factor
Kws = stator winding space factor	α = chording angle
δ = current density	Is / Ils = stator phase/ line current
Asc = area stator conductor	Diasc = diameter of stator conductor
Sbc = space required for bare conductor	Sf = space factor
Aslot = slot area	Wtsmin = minimum width of stator slot
Li = iron length	dss = depth of stator slot
Btm = maximum allowable flux density in teeth	Wts = actual width of stator teeth
AAs = slot width of stator lower side	AAsb = slot width of stator upper side
h = height of slot	Sbc = Zss * Asc
Sr = no. of rotor slots	Ysr = rotor slot pitch
Irb = current in rotor bars	Arb = area of rotor bar

δb = current density in rotor bar	Wsr / Dsr = width / depth of rotor slot
Spitch = slot pitch	Wt = width of teeth
Bt = flux density in teeth	Lb = length of bar
rb = resistance of rotor bar	Ie = end ring current
Dec / Ae = depth / area of end ring	de / te = sides of the ring
Culosse = copper losses in end ring	rcl= rotor copper losses
dcr = depth of rotor core	Bcr =flux density in rotor core
Di = inside dia. of rotor core	Doe /Die = outside & inside diameter of end ring
Culoss = copper loss in rotor bar	Bt = flux density in stator teeth
Φcs /Bcs = flux and flux density in stator core	Acs /dcs = area/ depth of stator core
Do = outside diameter of stator laminations	lg = length of air gap
Dr = diameter of rotor	Sr = no. of rotor slots
Ysr = rotor slots pitch	sos = stator slots opening
Kcs = carter□s coefficient	Kgss / Kgsr = gap contraction factor for stator slot- rotor slots for opening
Kgs = total gap contraction factor	Kg = gap contraction factor
ATg = air gap mmf	Atp = area of teeth per pole
atts = mmf per metre height of stator teeth	ATts = stator teeth mmf
atcs = mmf per metre height of stator core	lcs = mean length of magnetic path in stator core
ATcs = mmf in stator core	atr = mmf per metre height of rotot teeth
ATtr = rotor teeth mmf	lcr = mean length of magnetic path in rotor core
atcr = mmf per metre height of rotor core	ATcr = mmf in rotor core
AT = total mmf	Im = magnetizing current
Vst / Vsc = volume of stator teeth / core	Wst / Wsc = weight of stator teeth / core
Bmt = maximum flux density in teeth	Ist / Isc = iron loss of stator teeth / core
Iloss = total iron loss	FWls = friction and windage losses
NLoss= no load loss	Il = loss component of current
Io = no-load current	pfn = no-load power factor
Lmts = mean length of stator flux path	rs = stator resistance
scl= stator copper losses	LOSS = total losses
Eff = efficiency	

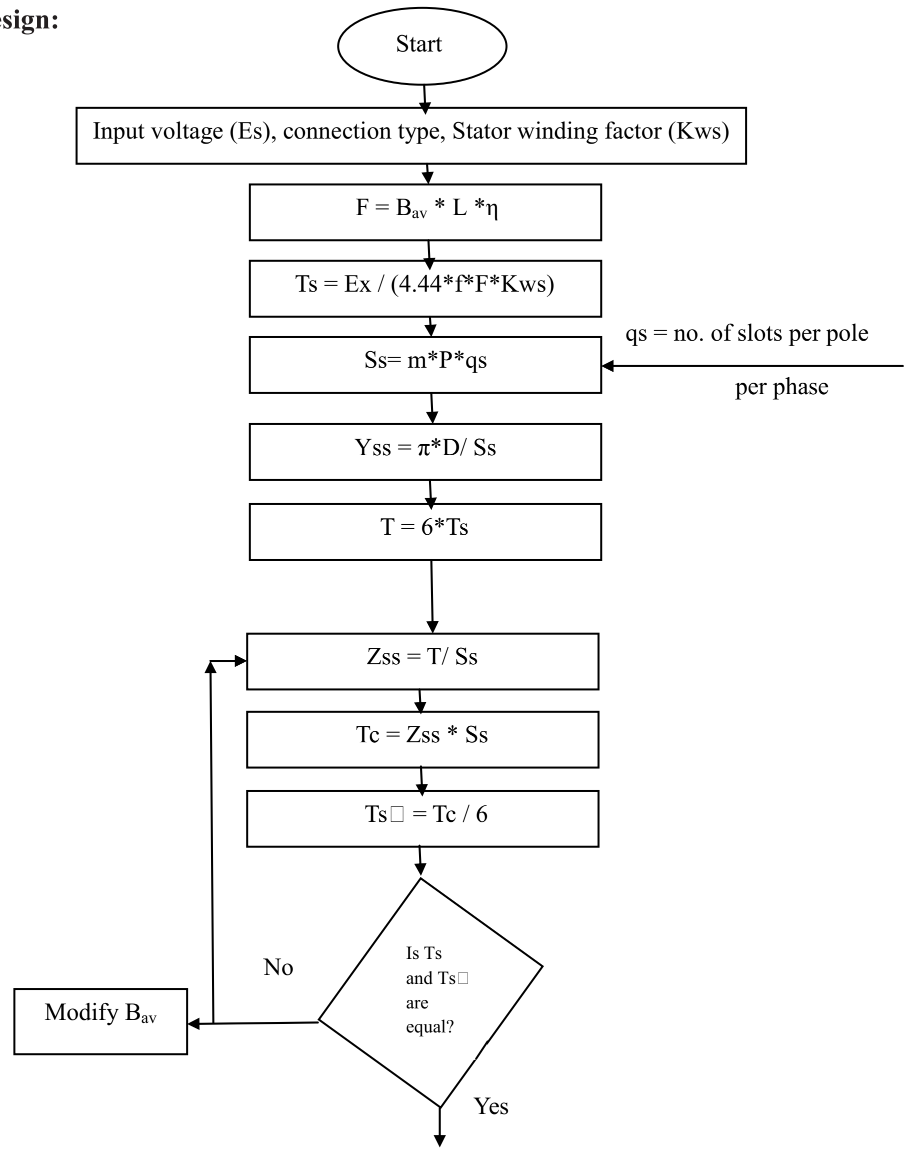
1.7.3 Flow charts for induction motor design:

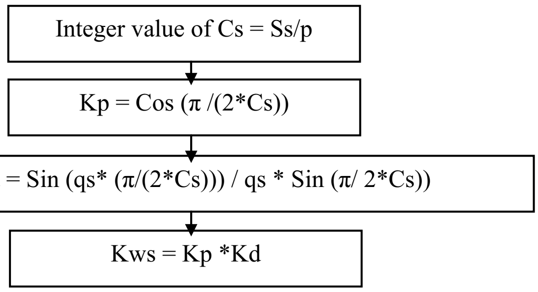
Main Dimensions:



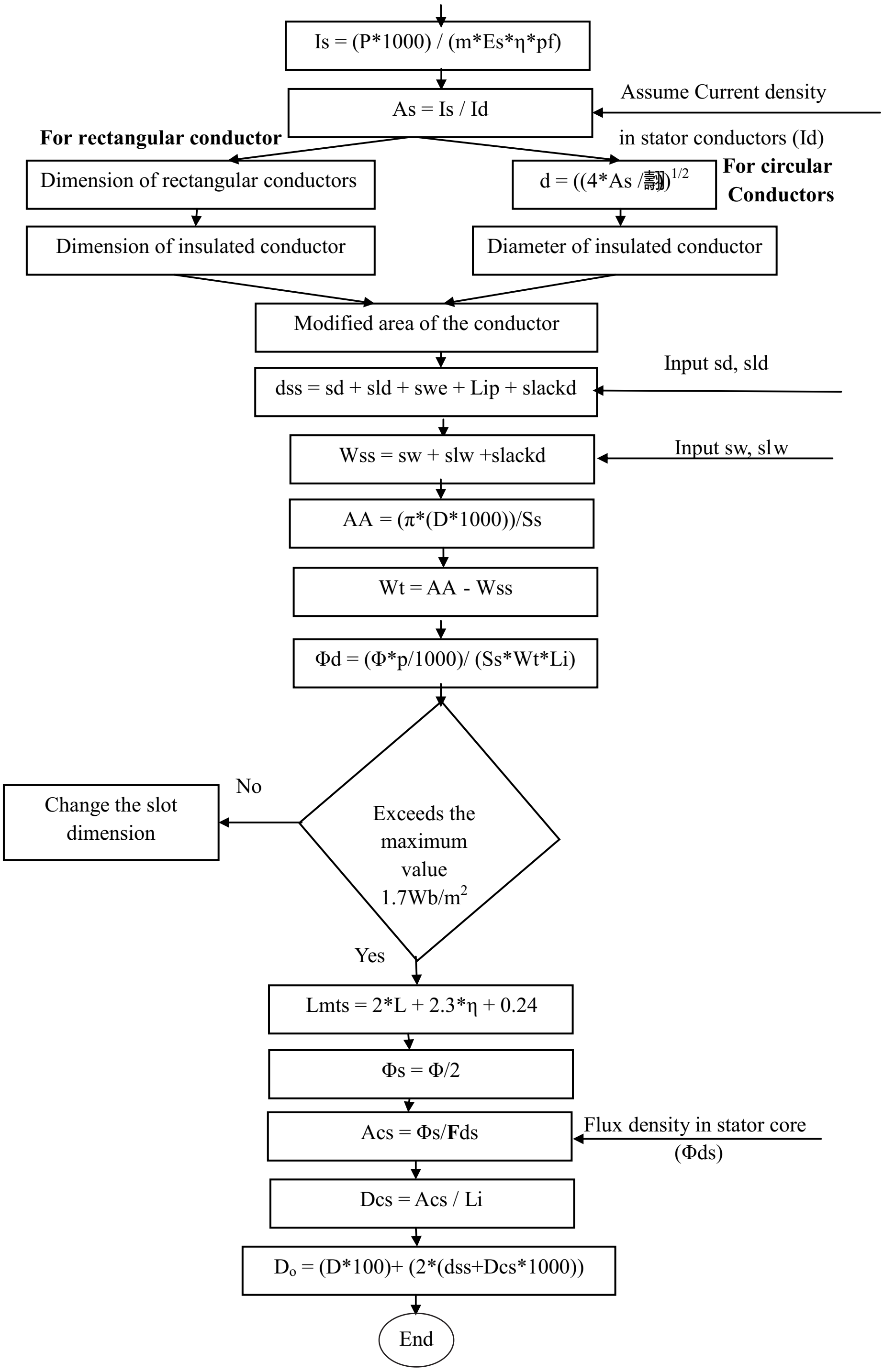


Start **Stator Design:**





Start **Stator Design:**



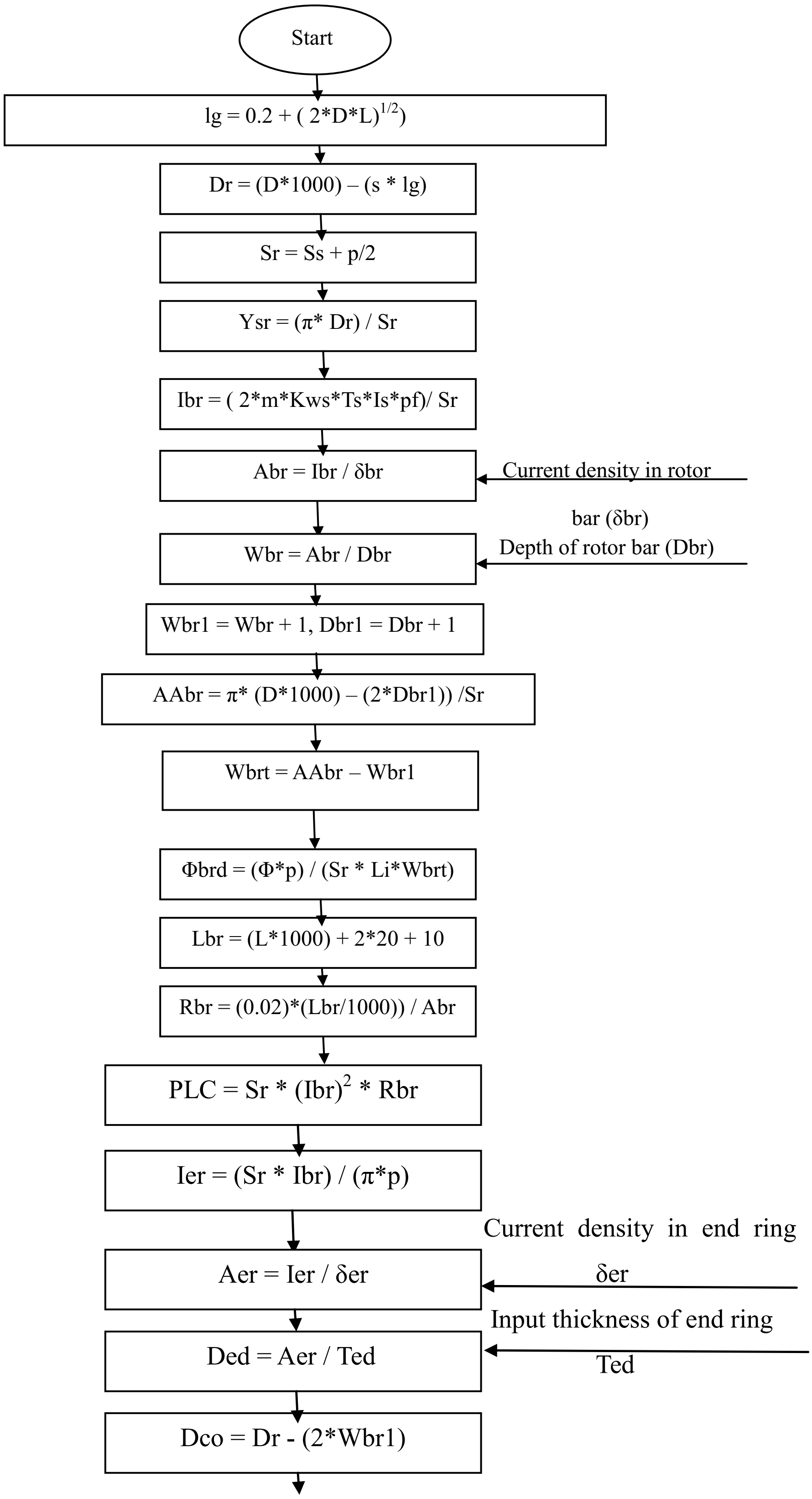
where, sd = no. of conductor in depth.

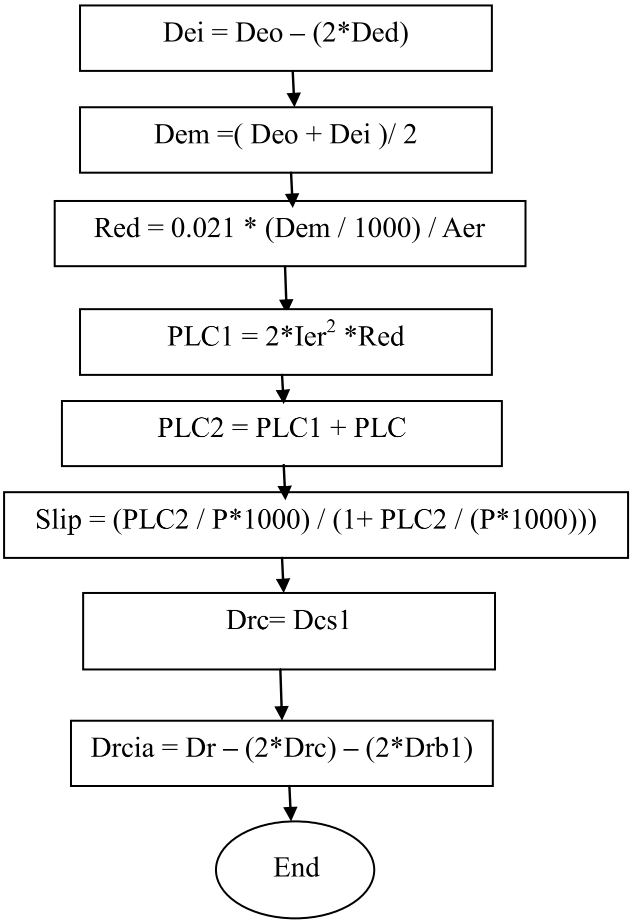
sId = insulation along depth of the conductor.

sw = no. of conductor in width

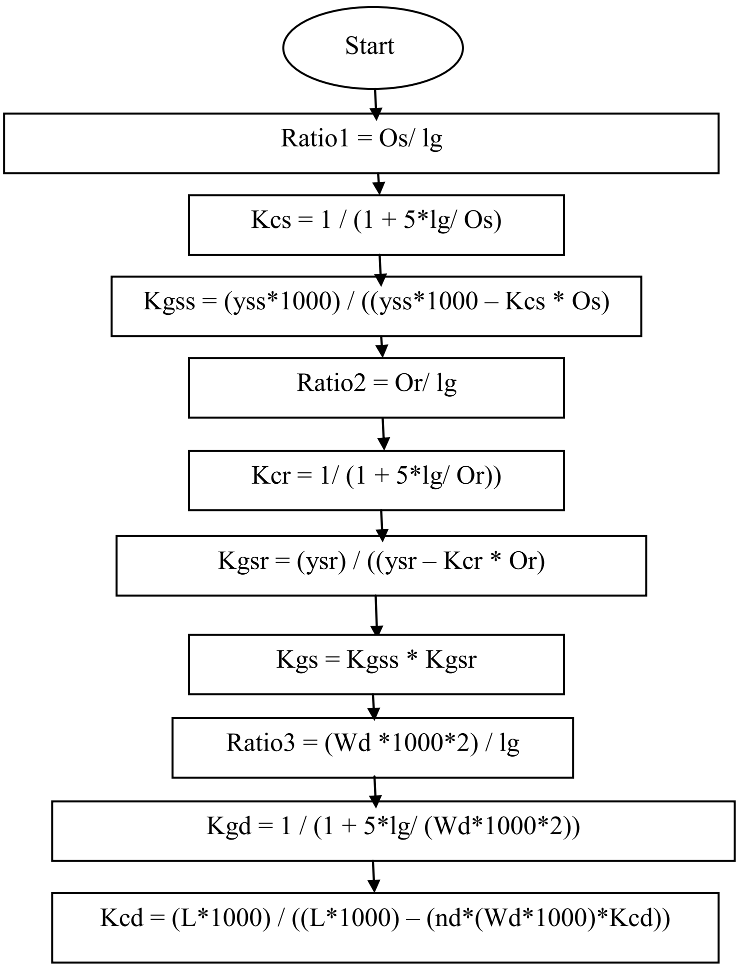
sIw = insulation along width of the conductor.

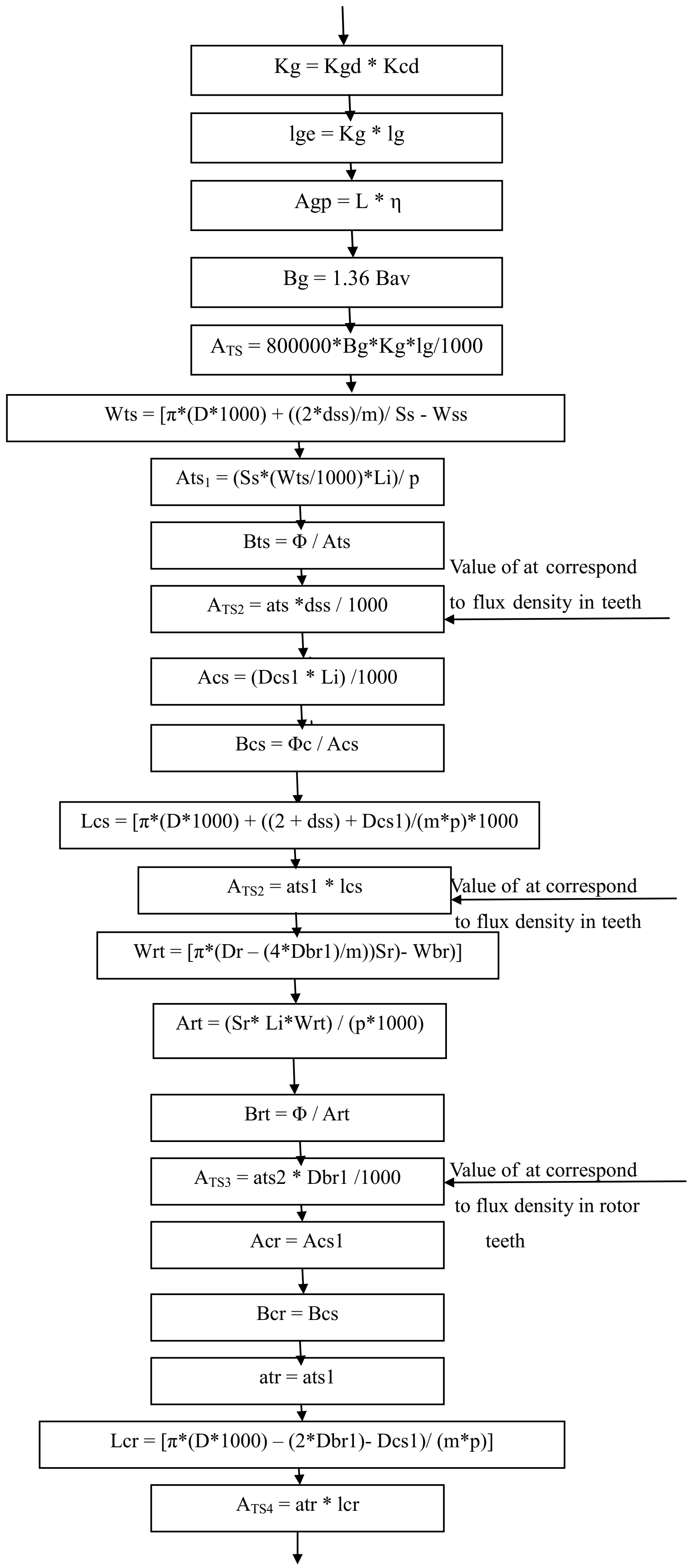
Start **Rotor Design:**

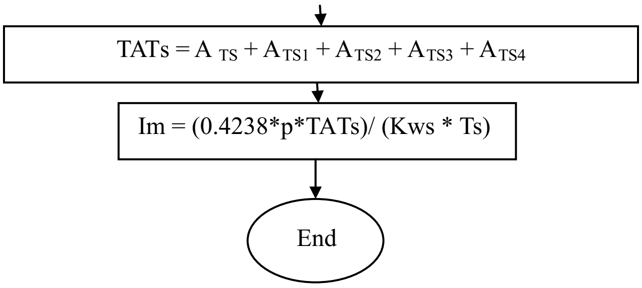




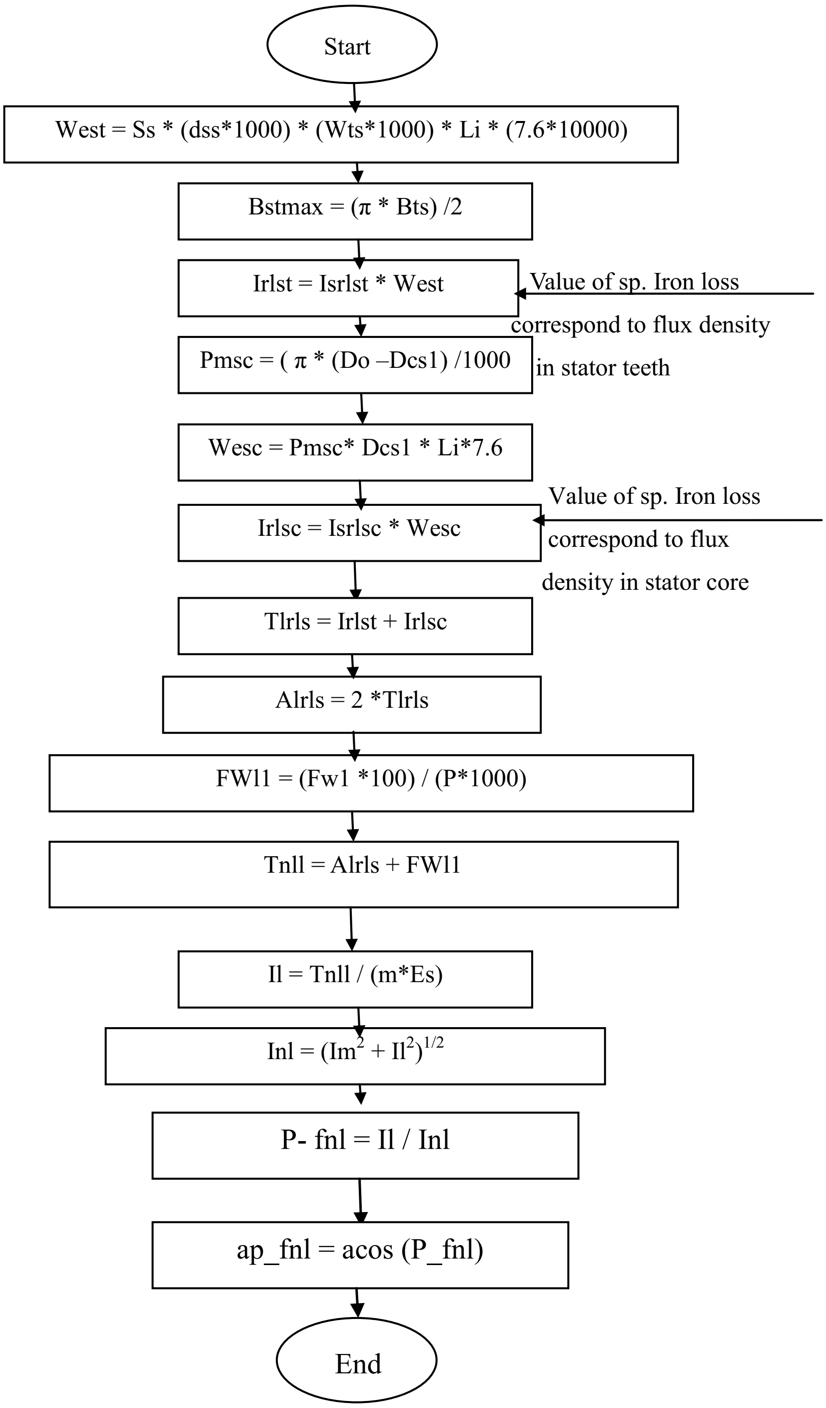
No Load current:



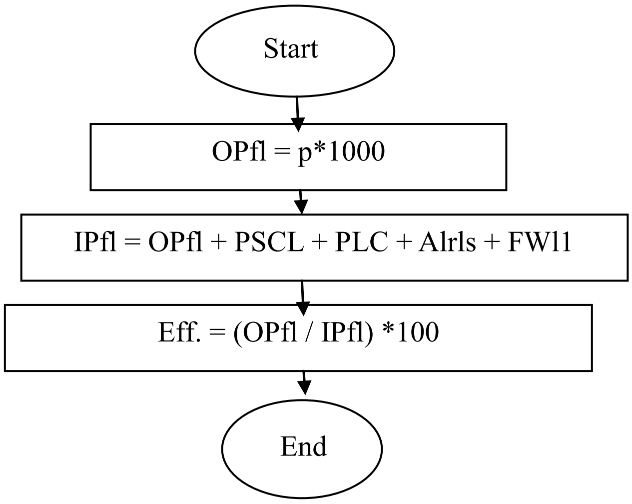

Kg = Kgd * Kcd
lge = Kg * lg
Agp = L * η
Bg = 1.36 Bav
ATS = 800000*Bg*Kg*lg/1000
Wts = [π*(D*1000) + ((2*dss)/m)/ Ss - Wss
Ats1 = (Ss*(Wts/1000)*Li)/ p
Bts = Φ / Ats
Value of at correspond
to flux density in teeth
ATS2 = ats *dss / 1000
Acs = (Dcs1 * Li) /1000
Bcs = Φc / Acs
Lcs = [π*(D*1000) + ((2 + dss) + Dcs1)/(m*p)*1000
ATS2 = ats1 * lcs
Value of at correspond
to flux density in teeth
Wrt = [π*(Dr – (4*Dbr1)/m))Sr)- Wbr)]
Art = (Sr* Li*Wrt) / (p*1000)
Brt = Φ / Art
ATS3 = ats2 * Dbr1 /1000
Value of at correspond
to flux density in rotor
teeth
Acr = Acs1
Bcr = Bcs
atr = ats1
Lcr = [π*(D*1000) – (2*Dbr1)- Dcs1)/ (m*p)]
ATS4 = atr * lcr



Loss Component:



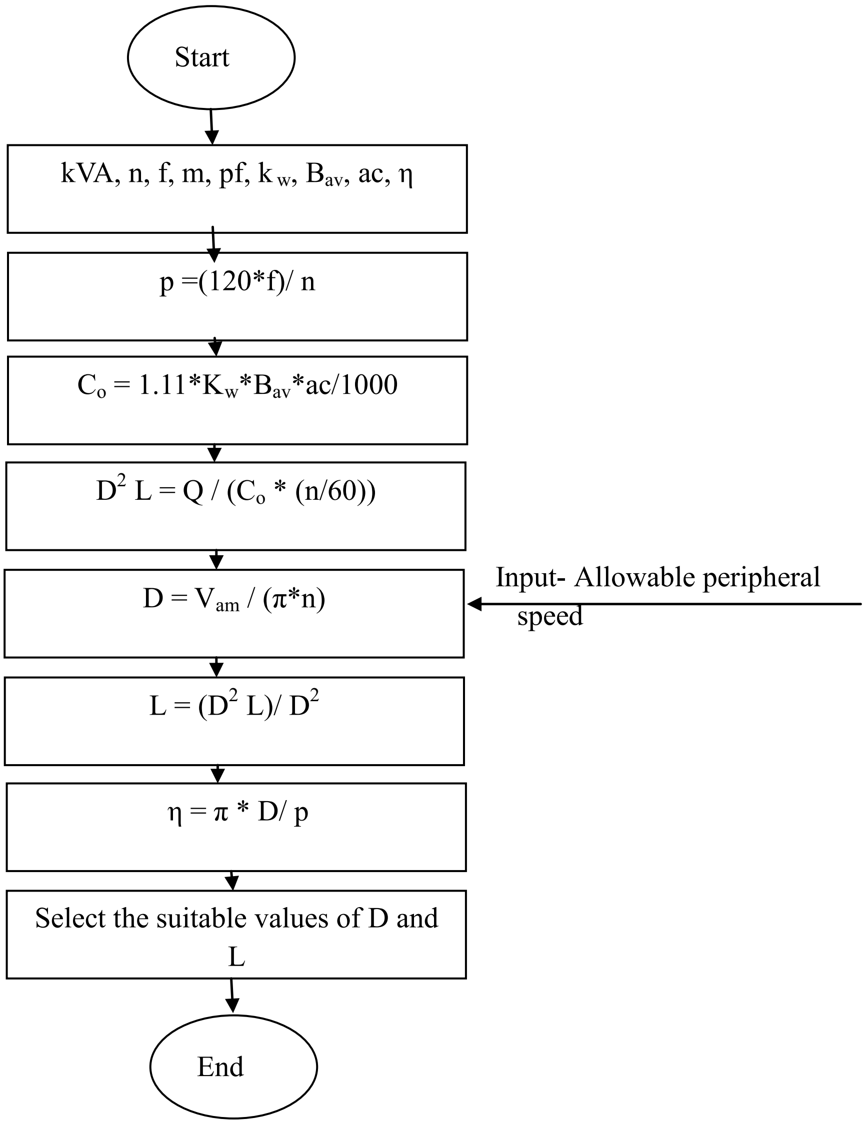
Efficiency:



1.8 COMPUTER AIDED DESIGN OF SYNCHRONOUS MACHINE

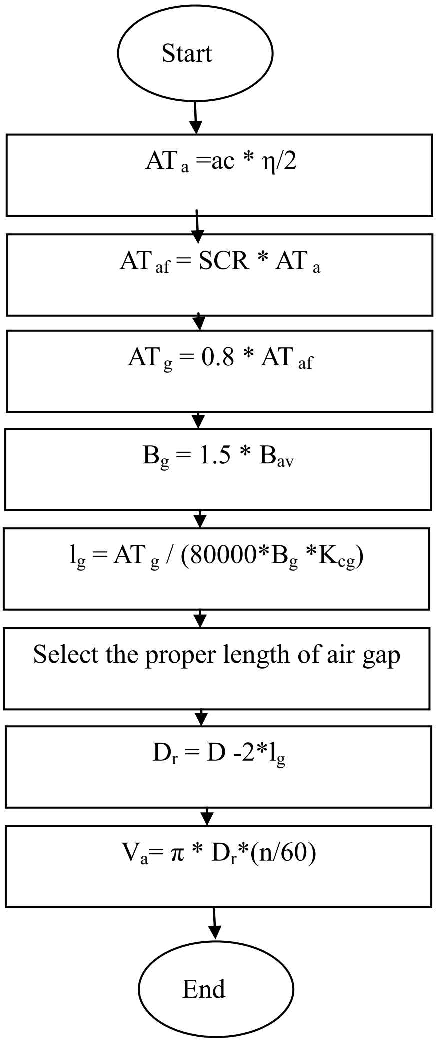
1.8.1 Flow Charts Computer Aided design of synchronous machine is as under

Main dimensions:



Note: The value of maximum peripheral speed is 175m/sec. and its normal value is 120m/sec.

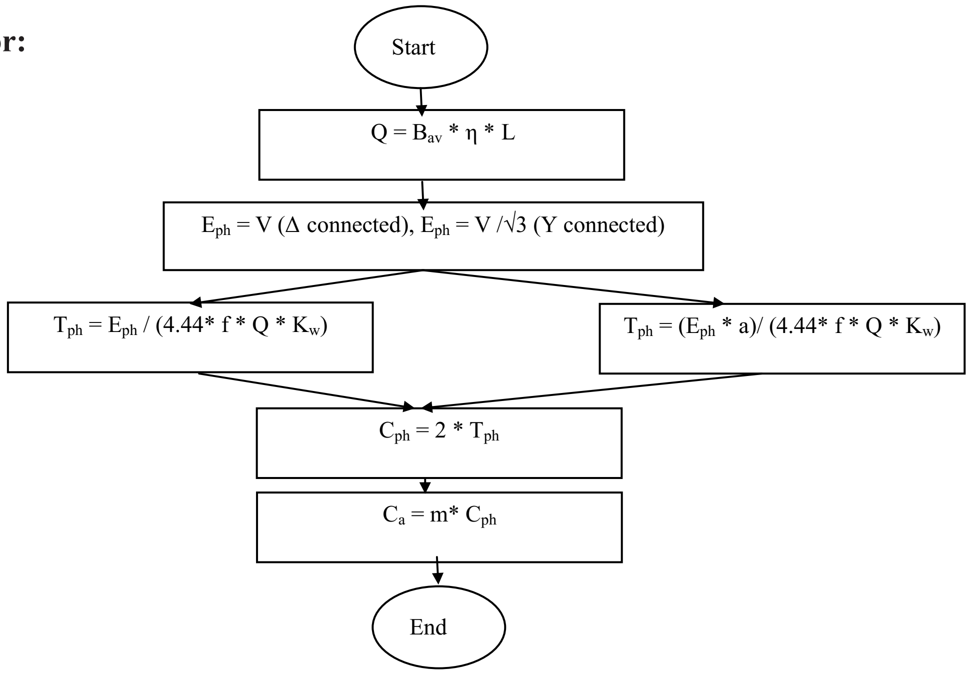
Length of air gap:



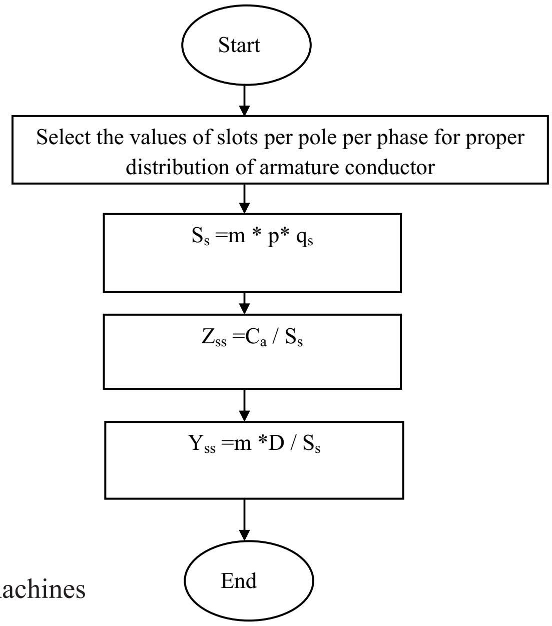
Note:

1. The short circuit ratio of the machine is 0.5 to 0.7
2. The ratio of air gap mmf to no-load mmf is constant value (80%).
3. The gap contraction factor is always 1.1

Start **Stator:**



Number of Slots:

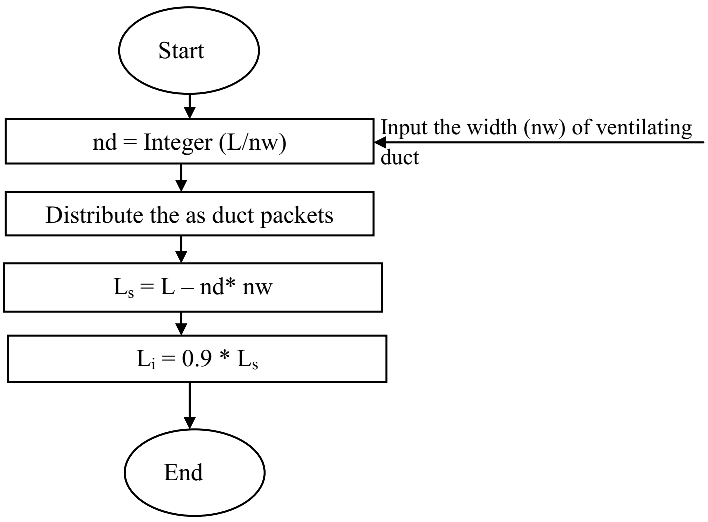


Yss = 25 for low voltage machines

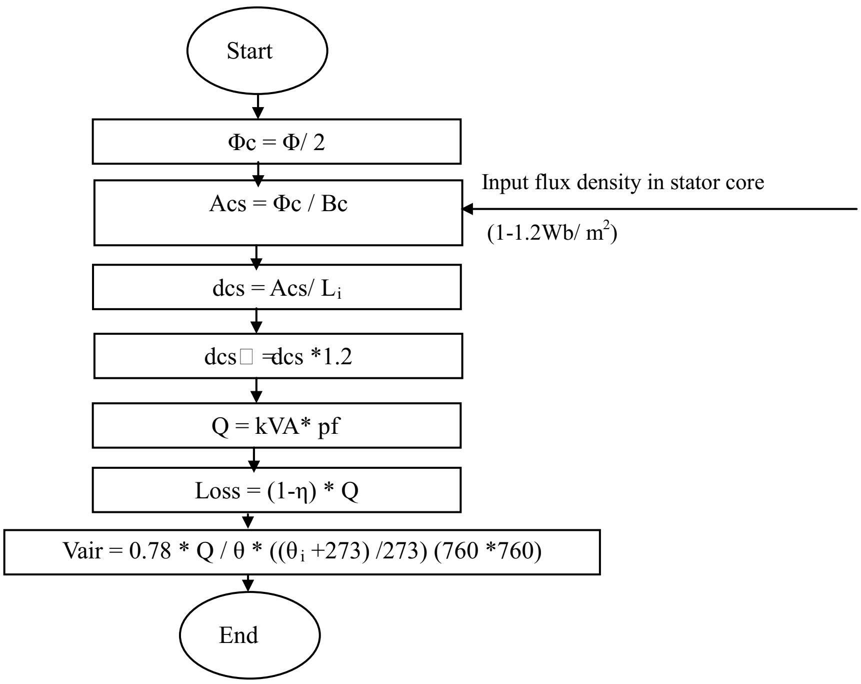
Yss = 40 for 6kV

Yss = 60 upto 15kV

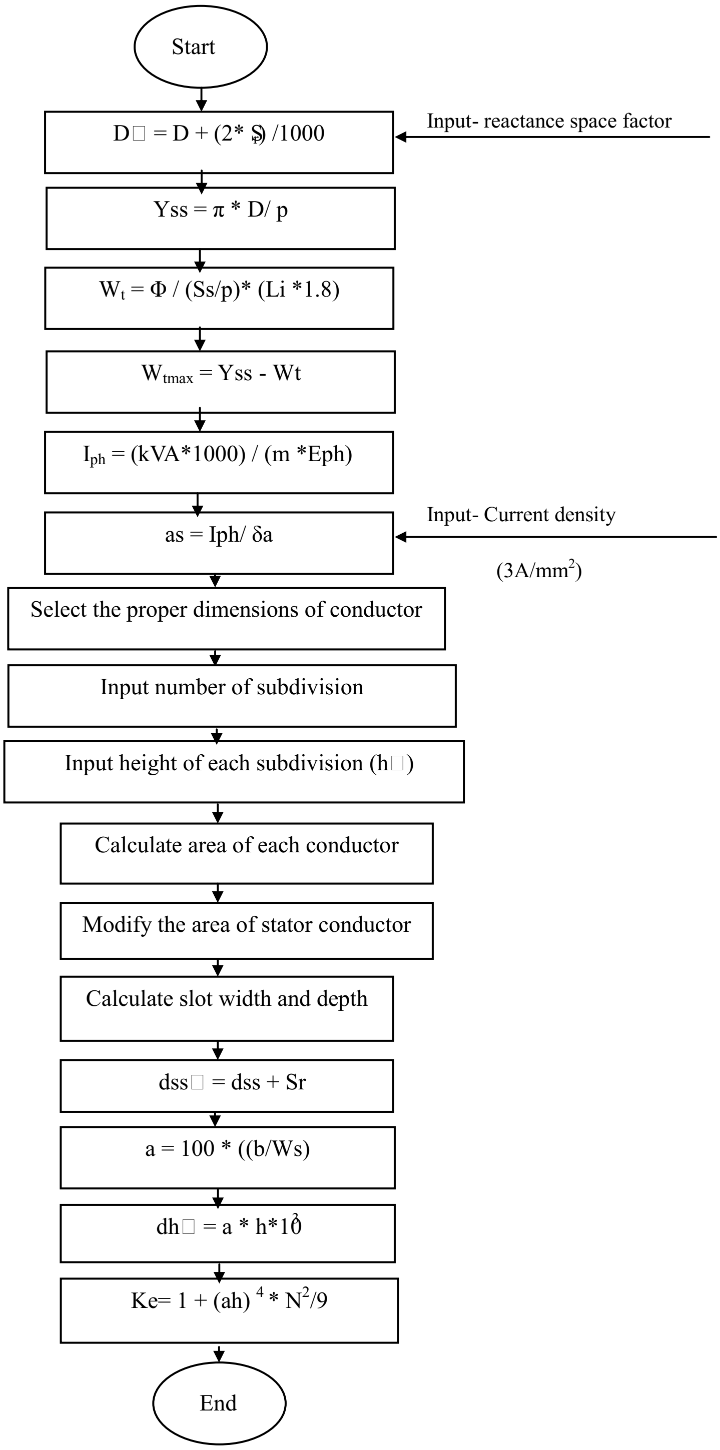
Magnetic Circuit:



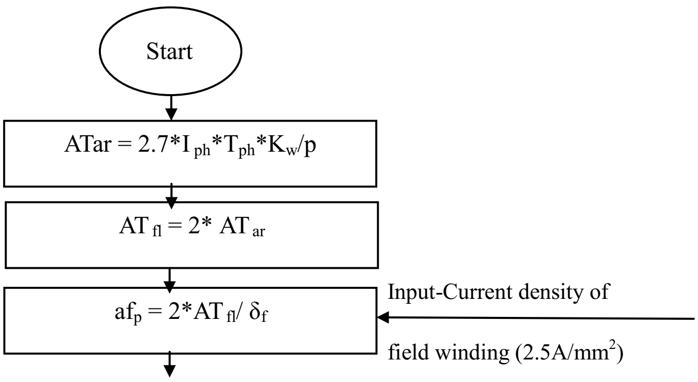
ix) Stator Core:

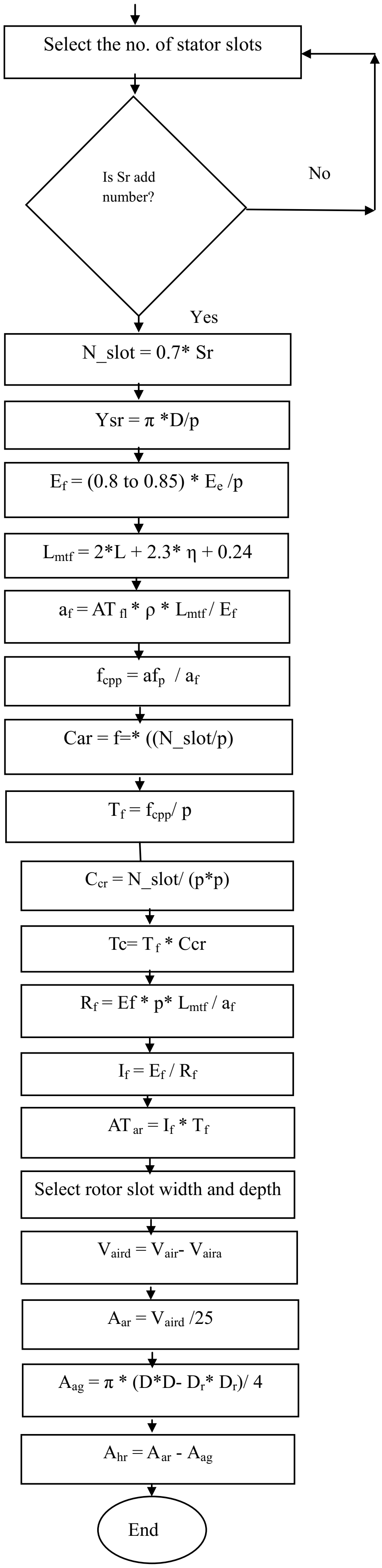


Slot dimensions:



Rotor design:




Select the no. of stator slots
Is Sr add number?
No
Yes
N_slot = 0.7* Sr
Ysr = π *D/p
E_f = (0.8 to 0.85) * E_e /p
L_{mtf} = 2*L + 2.3* η + 0.24
a_f = AT_{fl} * ρ * L_{mtf} / E_f
f_{cpp} = af_p / a_f
Car = f=* ((N_slot/p)
T_f = f_{cpp}/ p
C_{cr} = N_slot/ (p*p)
Tc= T_f * Ccr
R_f = Ef * p* L_{mtf} / a_f
I_f = E_f / R_f
AT_{ar} = I_f * T_f
Select rotor slot width and depth
V_{aird} = V_{air}- V_{aira}
A_{ar} = V_{aird} /25
A_{ag} = π * (D*D- D_r* D_r)/ 4
A_{hr} = A_{ar} - A_{ag}
End

1.9 COMPUTER AIDED DESIGN OF DC MACHINE

1.9.1 Basic Aspects

The design features of a DC motor are

1. Main dimensions
2. Armature winding
3. Design of field winding
4. Design of commutator
5. Design of interpoles
6. Losses and efficiency

The most important parameter is frequency of flux reversal which directly proportional to the product of speed and poles of the machine. The range of frequency is 25-50Hz. Higher value of frequency causes excessive iron losses in the core and armature.

In the large machines, the difference between armature power and rate output power is negligible and thus $P_a = P$. But in small machines, the frictional and windage losses are 1/3rd of the total losses. So, the armature power, $P_a = P(2+\eta) / (3 * \eta)$, where η is efficiency of the motor. Output coefficient C_0 is determined by using the value of B_{av} (0.04Wb/m^2 to 1.1Wb/m^2), ac (15000A/m to 51000A/m). For a particular machine, the output power Pa is directly proportional to product of B_{av} and ac

The product of armature power and rpm can be used to the percentage of field current. If the field current is below 400A, wave winding with no. of parallel paths 2 is used and for other values of field current, lap winding with no. of parallel paths is equal to no. of poles.

The value of leakage coefficient can be selected and the flux density in the pole body lies between 1.2-1.7Wb/m^2. The equation for net iron length is $L_{pi} = 0.9L$.

Number of brushes is almost equal to the number of poles to avoid flashover which causes due to insufficient space between adjacent brush arm.

Length of air gap under the interpole is greater than that under the main pole and so, the gap contraction factor (K_{gi}) for interpole is smaller than K_g.

Current density in the interpole lies between 2.5 to 4A/mm^2. The value of ratio of pole pitch to pole arc is 0.64 to 0.72. The maximum voltage between adjacent commutator segments at load is to be within 30volts. This leads limitations in D and L values. Core length greater than 120mm may need ventilating ducts and these ducts are placed at 70mm intervals. Width of each duct is around 100mm.

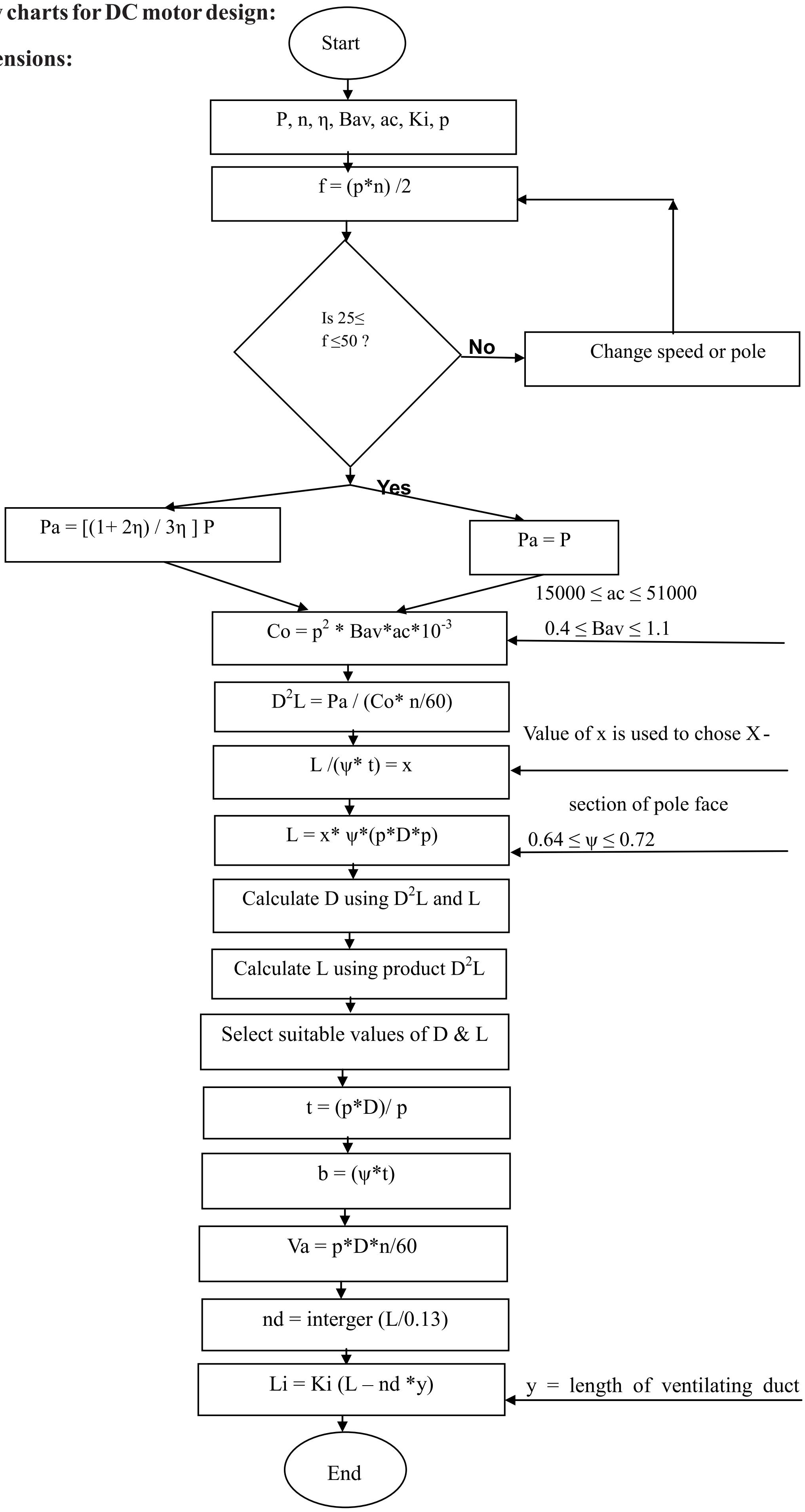
1.9.2List of Symbols used

Po = power output in kW	Q = kVA input
Vt = terminal voltage	eta = efficiency of the machine
n = speed, in r.p.sec.	P = no. of poles
Bg = max. gap density	ac = specific electric loading
Co = output coefficient	ψ(shy) = pole arc to pole pitch ratio
D = diameter of the core	L = length of core of the machine
Pa = generated armature power	τ = pole pitch
Ata = armature ampere turns	Atg = ampere turns required for air gap
Lg = length of air gap	Ia = armature current
Ib = brush current	Va = peripheral speed
F = frequency	Iline = line current
Ifield = field current	E = generated emf
Vdrop = voltage drop in armature $I_a r_a$	Z = no. of conductors
a = no. of parallel paths	Iz = current through the conductor
Cmin = minimum no. of coils	Smin. = minimum no. of slots
Smax = maximum no. of slots	Spitch = slots pitch
Spa = slots per pole arc	u = coil sides per slot
Tc = turns per coil	Coil = no. of coils

Z1 = no. of conductors	S1 = no. of slots
fxp = useful flux per pole	Bav = average flux density
Sload = slot loading	area = area of the conductor
ds = depth of slot	ins, insw = insulation depth & widthwise
Cops = conductor per slot	δa = current density in armature
Ws = slot width	m = no. of conductors depth-wise
m1 = no. of conductors width-wise	bare = space for bare conductor
D13 = diameter of $1/3^{rd}$ height of teeth	Wt = width of teeth at $1/3^{rd}$ height of teeth
Bt13 = flux density at $1/3^{rd}$ height from roof of the teeth	C1 = leakage coefficient
fyp = flux produced in the pole body	Bp = flux density in pole body
Ap = area of pole body	Lp = axial length of main pole
Lpi= net iron length of main core	Wp = width of main pole
df = depth of field winding	Sf = copper space factor
qf = permissible loss per m^3 of cooling surface.	Atfl = field mmf
Mh = mmf per metre height of the field winding	hf = height of field winding
hpl = total height of the pole	fy = flux in yoke
By = flux density in yoke	Ay, dy, Diay = area, depth and diameter of yoke
Kcs, Kcd = carter's coefficient for slot and ducts	Kgs = gap contraction factor for slots
Kgd = gap contraction factor for ducts	Kg = total gap contraction factor
nd = no. of ducts	wd= width of duct
att = mmf required per metre in teeth	ATt = total mmf required for teeth
dc = depth of the core	lc = length of the core
atp = mmf required per metre for pole	ATp = total mmf required for pole
aty = mmf required per metre in yoke	ATy = total mmf required for yoke
ly = length of flux path in yoke	ATf = total field mmf required for no-load
Ef = voltage across each field coil	Lmt = length of mean turn
ρ = resistivity of copper	af = area of field conductor
θ = temperature rise in field	Tf = no. of turns in field winding
Rf = resistance of each field coil	Qf = loss in each field coil
Sc = cooling surface	Cc= cooling coefficient
Dc = diameter of the commutator	βc = pitch of commutator segments
Vc = peripheral speed of commutator	Ab = area of each brush
δb = current density in the brushes	Tb = thickness of each brush
Wb = width of each brush	Cb = clearance between brushes
c1 = staggering	c2 = end play
Lc = length of the commutator	Pbc = brush contact drop
μ = coefficient of friction	temp = temperature rise in brush
Pb = brush pressure	Pbf = brush friction loss
Sbc = barrel surface area	Pbef = bearing friction and windage losses
Ptf = total friction and windage losses	Tm = mean width of teeth
Wat/ Wac = weight of teeth and core	Irst/Wac= specific iron loss in teeth and core
It = total iron loss	Lmta = length of mean turn of armature
ra = resistance of armature	Tloss= total loss
Closs = copper loss	Wb= brush contact loss
Wf = field copper loss	Eff, η = efficiency
Di = inside diameter of armature	Vai = peripheral speed of the inner side of armature
Tld = total loss dissipation of armature	Ldo / Ldi = outside and inside loss dissipation of the armature
So / Si = outside and inside surface area of the armature	Tempa = temperature rise in armature

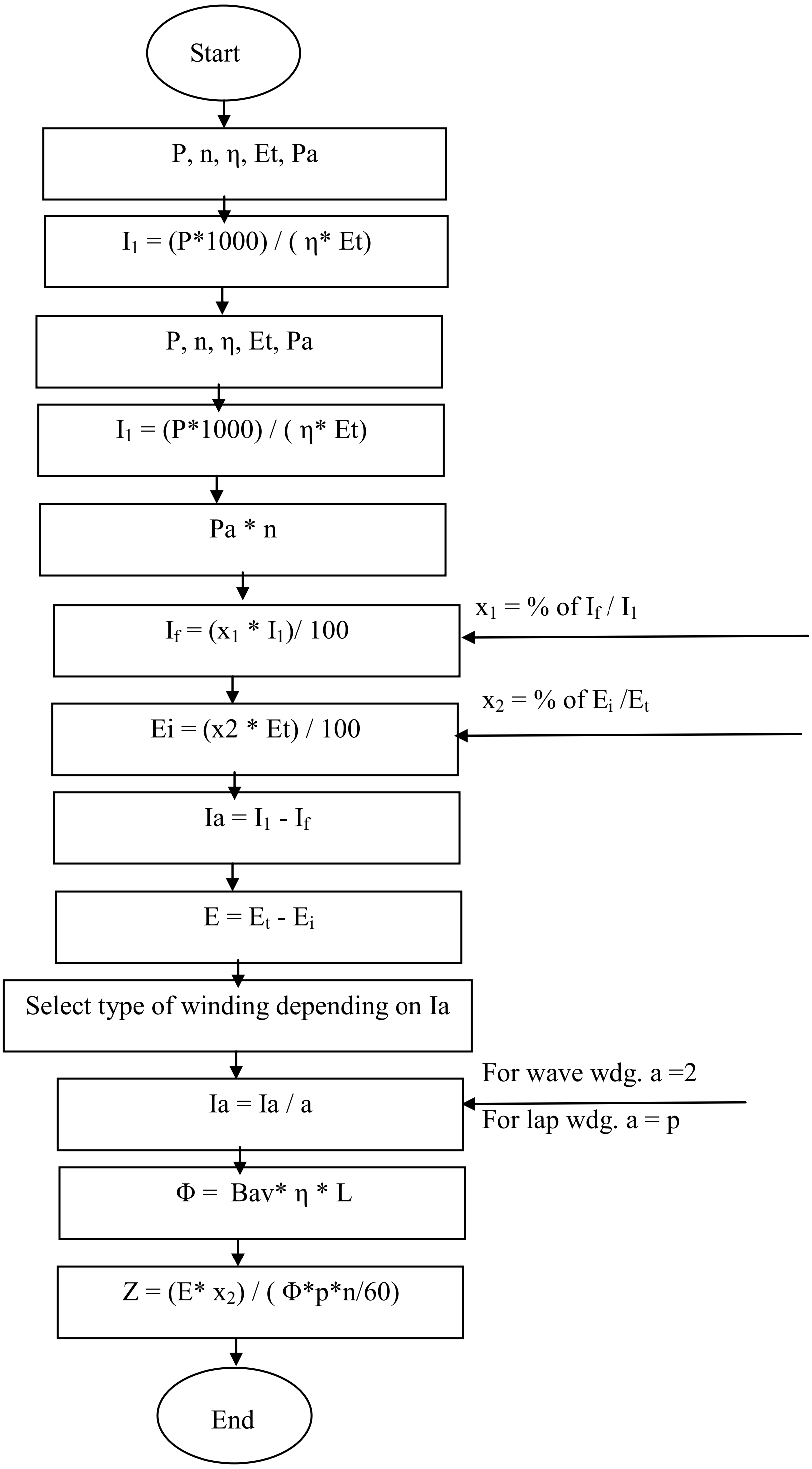
1.9.3 Flow charts for DC motor design:

Main Dimensions:



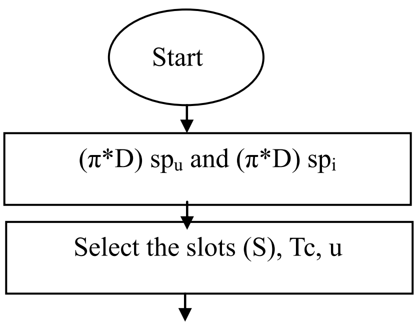
Note: p = no. of poles, b = pole arc, bp = pole width

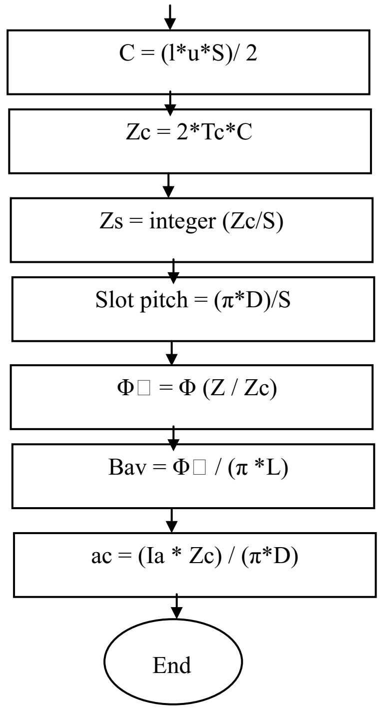
Armature winding:



Note: E_t= terminal voltage, E_1 = Voltage drop, E_i = back emf, Φ = flux per pole

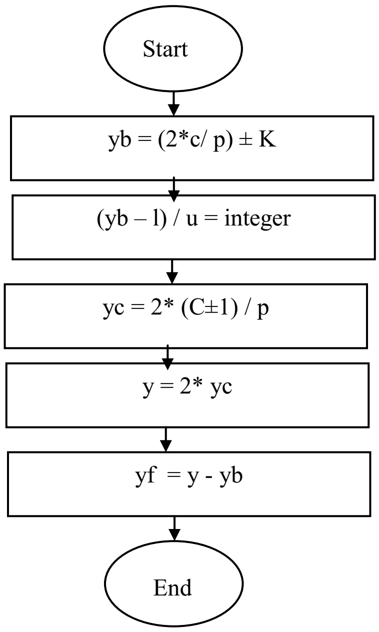
Number of slots:





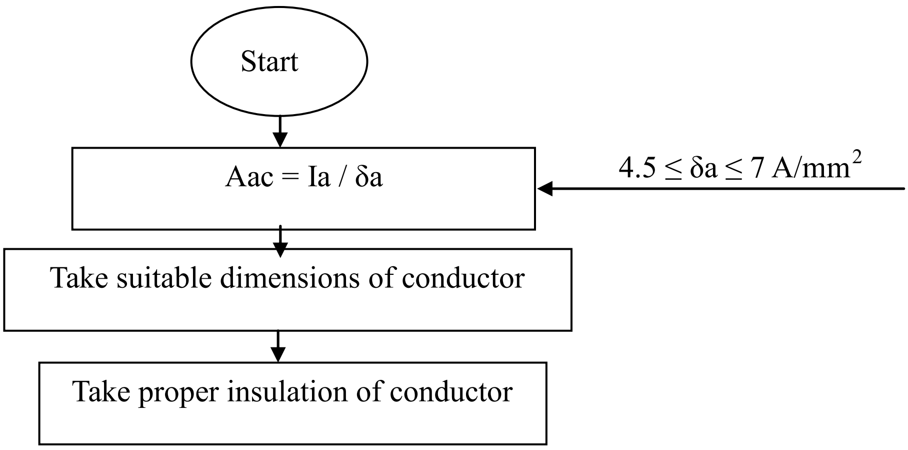
Note: Zc= total no. of armature conductors, u = coil side per slot, Tc = turn in a coil

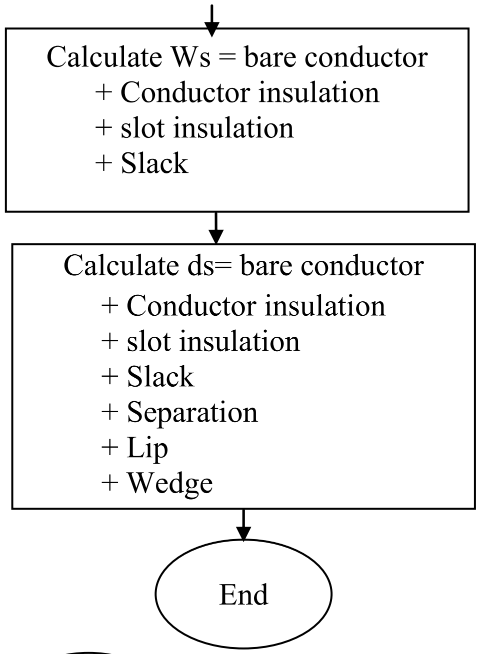
Winding Layout:



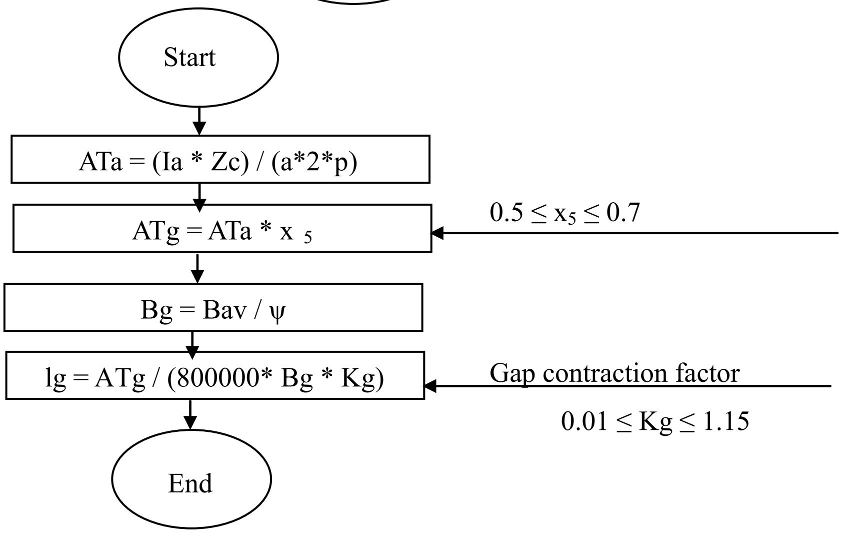
Note: yb is so selected in such a way that the back pitch (yb – 1) / coil per slot (u) should be an integer.

Design of Slots:

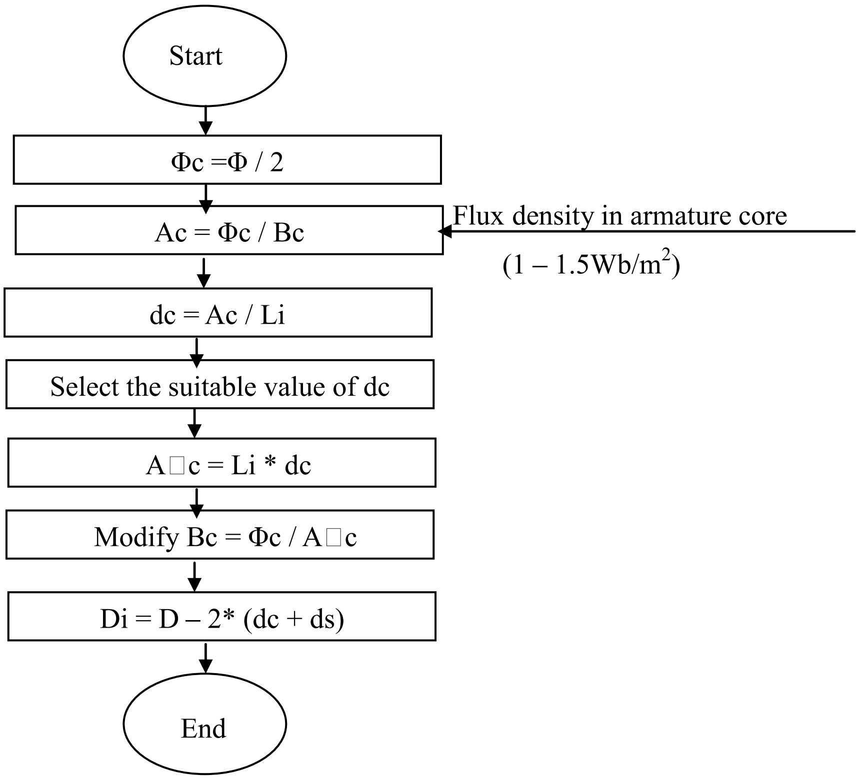




Lenght of air gap:

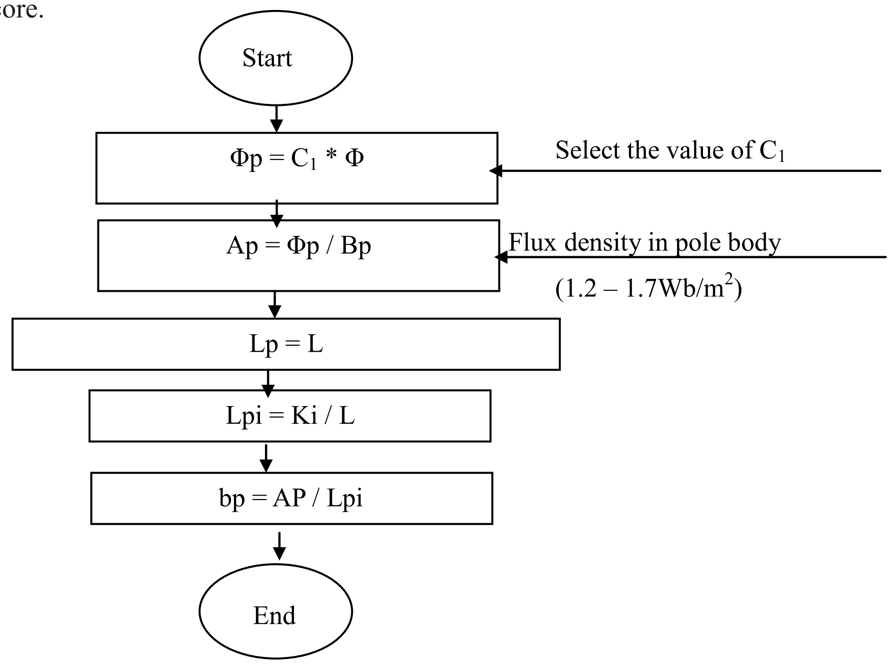


Armature Core:



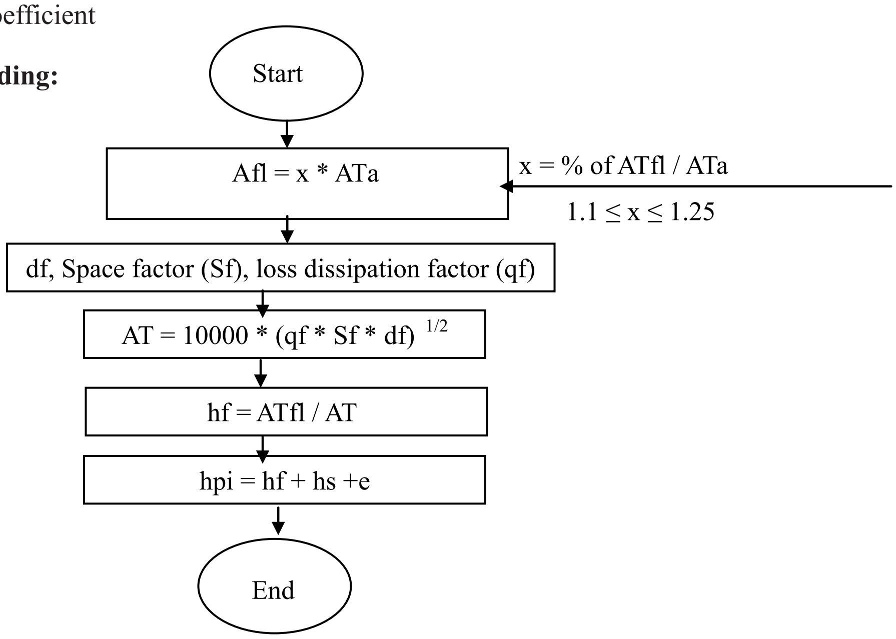
Note: Ac = area of armature core.

Pole Section:



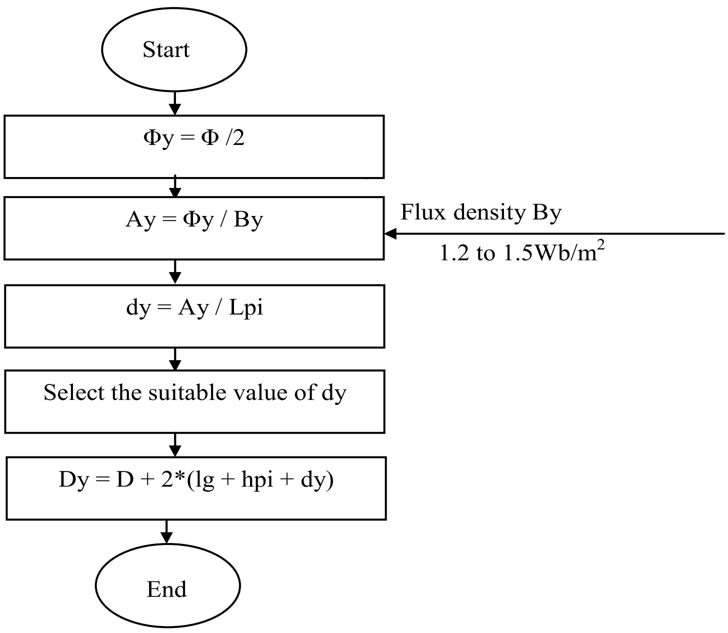
Note: C_1 = leakage coefficient

Design of Field Winding:

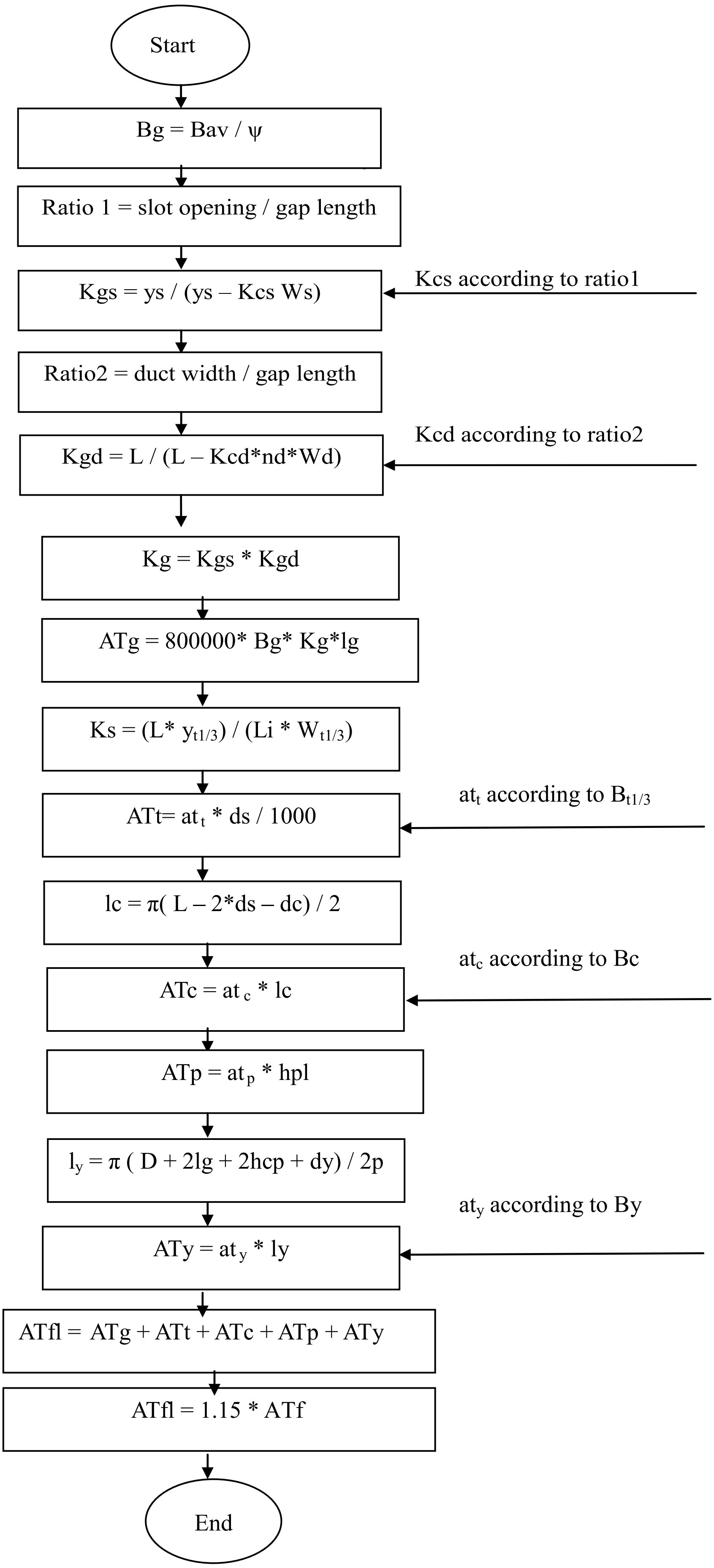


Note: hs = height of pole shoe = 0.1 to 0.2 of height of pole, e = height taken by insulation and space due to yoke.

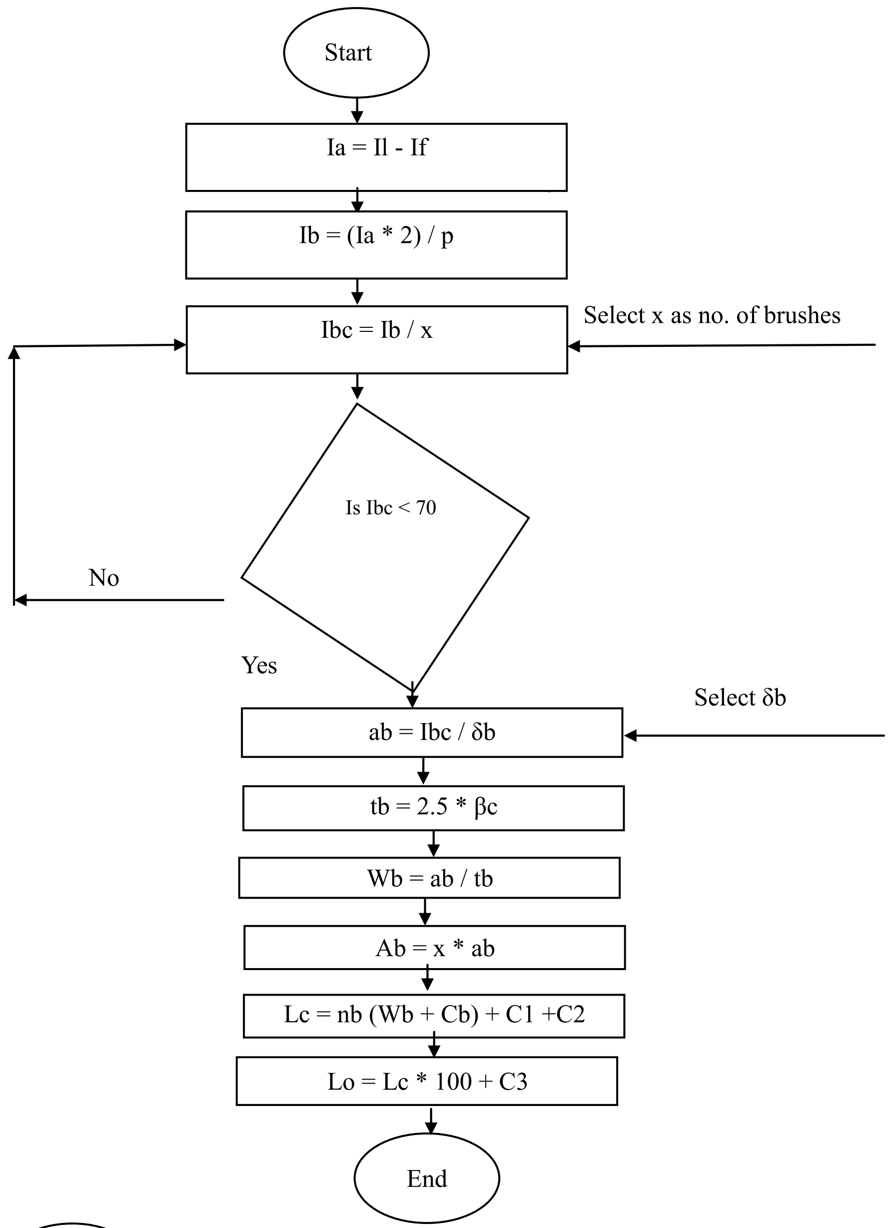
Yoke:



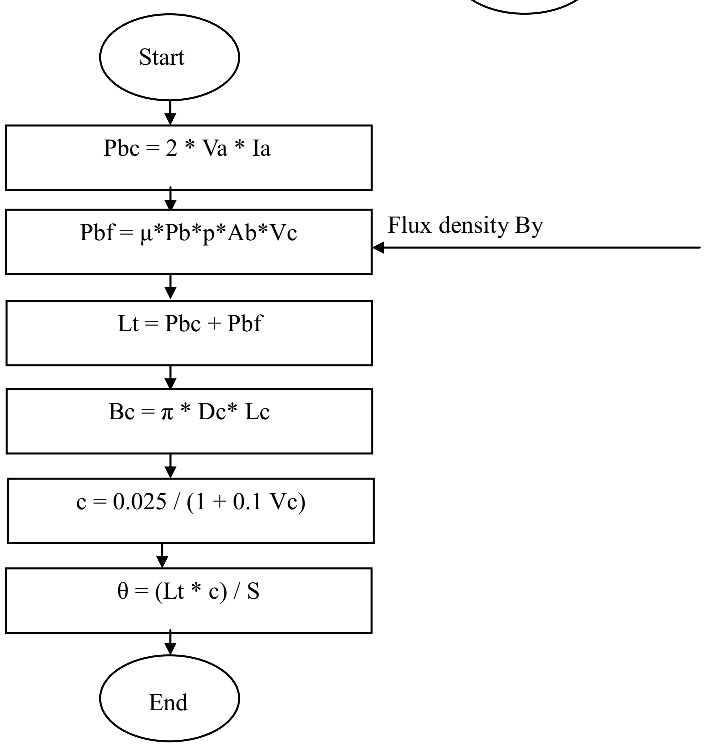
Magnetic Circuit:



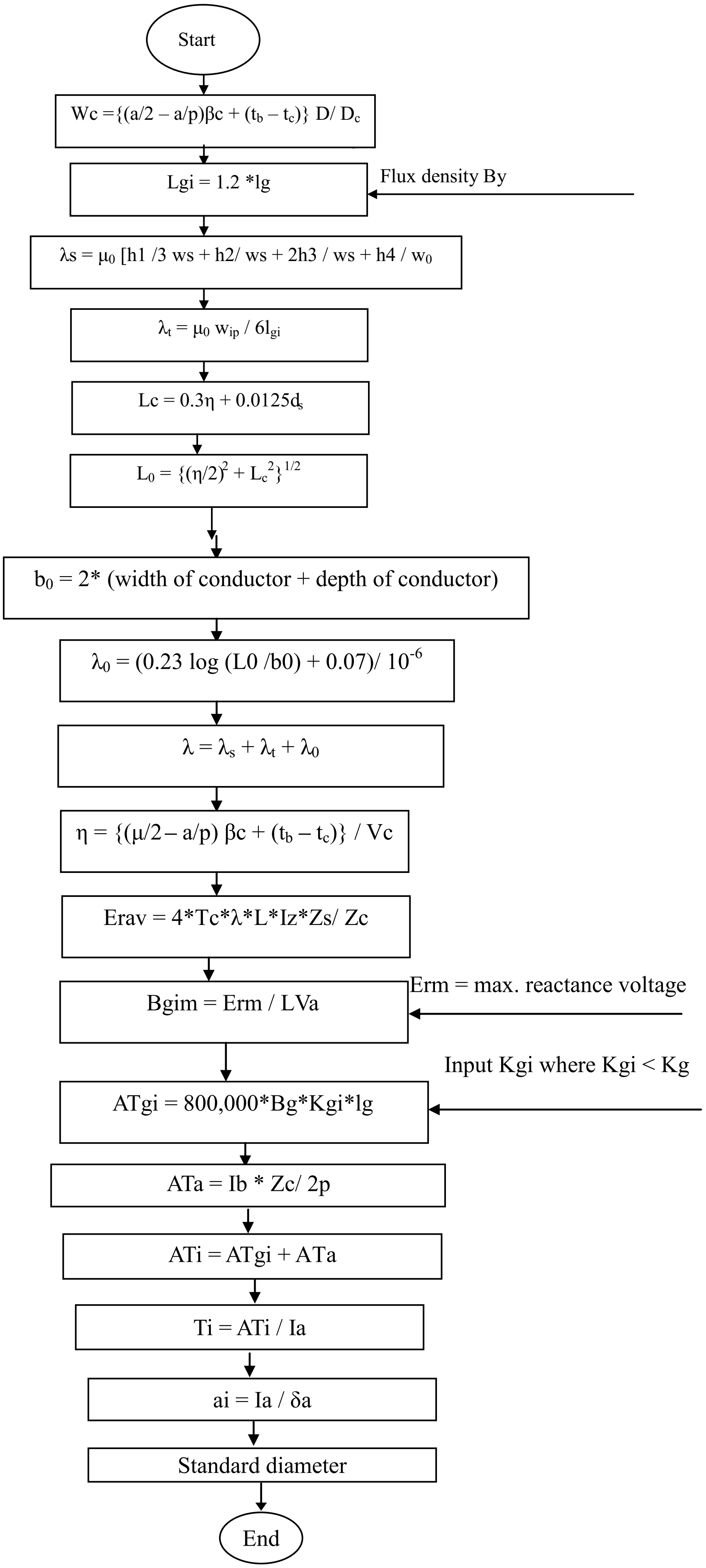
Brushes:



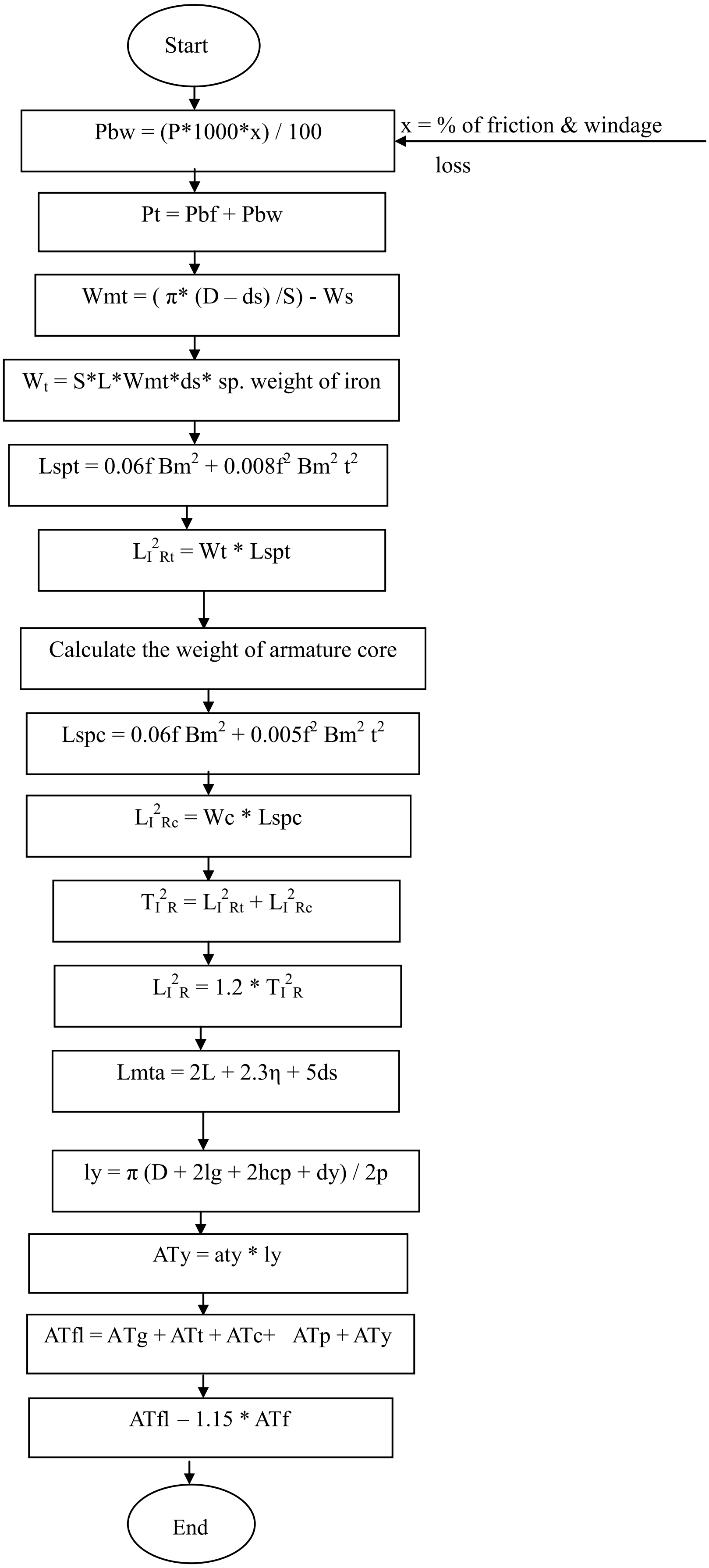
Losses:



Design of Interpoles:



Losses and Efficiecny:



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