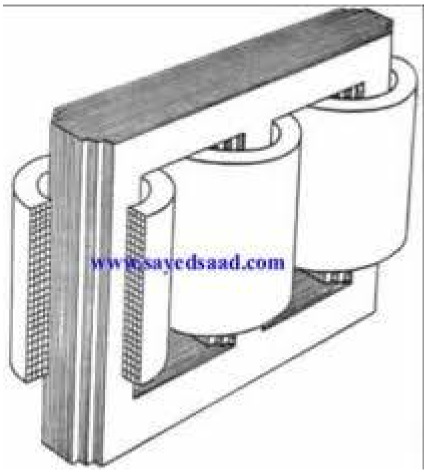
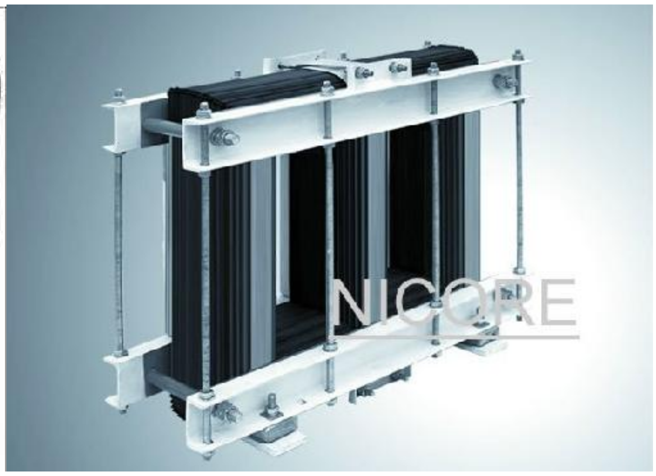
Transformer Design

(© Dr. R. C. Goel & Nafees Ahmed)





By

Nafees Ahmed

Asstt. Prof. Department of Electrical Engineering
DIT, University, Dehradun, Uttarakhand

References:

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

<u>OUTPUT EQUATION: -</u> It gives the relationship between electrical rating and physical dimensions of the machines.

Let

V_1 = Primary voltage say LV
V_2 = Secondary voltage say HV
I_1 = Primary current
I_2 = Secondary current
N_1= Primary no of turns
N_2= Secondary no of turns
a_1 = Sectional area of LV conductors (m^2)

$$= \frac{I_1}{¢}$$

a_2 = Sectional area of HV conductors (m^2)

$$= \frac{I_2}{¢}$$

¢ = Permissible current density (A/m^2)
Q = Rating in KVA

We place first half of LV on one limb and rest half of LV on other limb to reduce leakage flux. So arrangement is LV insulation then half LV turns then HV insulation and then half HV turns.

(1) For 1-phase core type transformer

Rating is given by

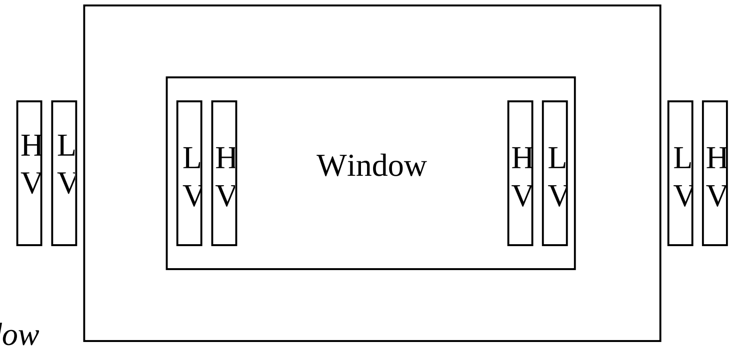
$$Q = V_1 I_1 \times 10^{-3} \quad \text{KVA}$$

$$= (4.44 f ¤_m N_1) I_1 \times 10^{-3} \quad \text{KVA} \qquad (\because V_1 = 4.44 f ¤_m N_1)$$

$$= 4.44 f (A_i B_m) N_1 I_1 \times 10^{-3} \quad \text{KVA} \quad \text{-----------(1)} \qquad (\because ¤_m = A_i B_m)$$

Where

f = frequency
$¤_m$ = Maximum flux in the core
A_i = Sectional area of core
B_m = Maximum flux density in the core



1-phase core type transformer with concentric windings

Window Space Factor

$$K_w = \frac{Actual\,Cu\,Section\,Area\,of\,Windings\,in\,Window}{Window\,Area\,(A_w)}$$

$$= \frac{a_1 N_1 + a_2 N_2}{A_w}$$

$$= \frac{(I_1/¢)N_1 + (I_2/¢)N_2}{A_w} \qquad (\because a_1 = I/_1¢ \,\&\, a_2 = I/_2¢)$$

$$= \frac{I_1 N_1 + I_2 N_2}{¢ A_w}$$

$$= \frac{2 I_1 N_1}{¢ A_w} \qquad (For\,Ideal\,Transformer\; I_1 N_1 = I_2 N_2)$$

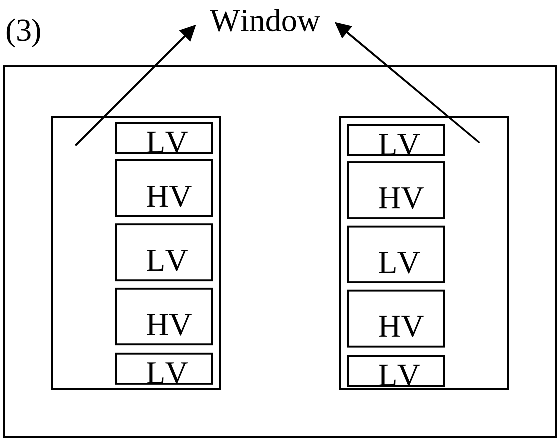
So

$$\left[N_1 I_1 = \frac{¢ K_w A_w}{2} \right] \quad -------------- (2)$$

Put the value of $N_1 I_1$ form equation (2) to equation (1)

$$Q = 4.44\, f\, A_i\, B_m \frac{¢\, K_w\, A_w}{2} \times 10^{-3} \qquad KVA$$

$$\boxed{Q = 2.22\, f\, A_i\, B_m\, ¢\, K_w\, A_w \times 10^{-3} \qquad KVA} \quad ---------- (3)$$



1-phase shell type transformer with sandwich windings

(2) For 1- phase shell type transformer

Window Space Factor

$$K_w = \frac{a_1 N_1 + a_2 N_2}{A_w}$$

$$= \frac{(I_1/¢)N_1 + (I_2/¢)N_2}{A_w} \qquad (\because a_1 = I/_1¢ \;\&\; a_2 = I/_2¢)$$

$$= \frac{I_1 N_1 + I_2 N_2}{¢ A_w}$$

$$= \frac{2 I_1 N_1}{¢ A_w} \qquad (For\ Ideal\ Transformer\ \ I_1 N_1 = I_2 N_2\ )$$

So

$$N_1 I_1 = \frac{¢ K_w A_w}{2} \quad --------------- (4)$$

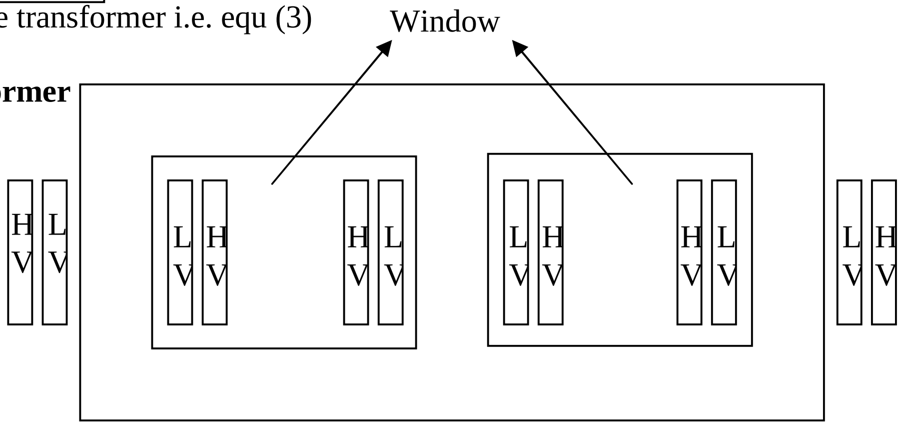
Put the value of $N_1 I_1$ form equation (4) to equation (1)

$$Q = 4.44\, f\, A_i\, B_m \frac{¢\, K_w\, A_w}{2} \times 10^{-3} \qquad KVA$$

$$\boxed{Q = 2.22\, f\, A_i\, B_m\, ¢\, K_w\, A_w \times 10^{-3} \qquad KVA} \quad -------- (5)$$

Note it is same as for 1-phase core type transformer i.e. equ (3)

(3) For 3-phase core type transformer



3-phase core type transformer with concentric windings

Rating is given by

$$Q = 3 \times V_1 I_1 \times 10^{-3} \qquad KVA$$

$$= 3 \times (4.44\, f¤_m N_1) I_1 \times 10^{-3} \quad KVA \qquad (\because V_1 = 4.44\, f¤_m N_1)$$

$$= 3 \times (4.44\, f A_i B_m N_1) I_1 \times 10^{-3} \quad KVA \qquad -----------(6) \qquad (\because ¤_m = A_i B_m)$$

Window Space Factor

$$K_w = \frac{Actual\ Cu\ Section\ Area\ of\ Windings\ in\ Window}{Window\ Area\ (A_w)}$$

$$= \frac{2(a_1N_1 + a_2N_2)}{A_w}$$

$$= \frac{2 \times [(I_1/¢)N_1 + (I_2/¢)N_2]}{A_w} \qquad (\because a_1 = I/_1¢ \ \& \ a_2 = I/_2¢)$$

$$= \frac{2(I_1N_1 + I_2N_2)}{¢A_w}$$

$$= \frac{2 \times 2I_1N_1}{¢A_w} \qquad (For\ Ideal\ Transformer\ I_1N_1 = I_2N_2\ )$$

So

$$N_1I_1 = \frac{¢\ K_wA_w}{4} \quad --------------(7)$$

Put the value of N_1I_1 form equation (7) to equation (6)

$$Q = 3 \times 4.44\ f\ A_i\ B_m \frac{¢\ K_w\ A_w}{4} \times 10^{-3} \qquad KVA$$

$$\boxed{Q = 3.33\ f\ A_i\ B_m\ ¢\ K_w\ A_w \times 10^{-3} \qquad KVA} \quad ----(8)$$

(3) For 3- phase shell type transformer

Window Space Factor

$$K_w = \frac{a_1N_1 + a_2N_2}{A_w}$$

$$= \frac{(I_1/¢)N_1 + (I_2/¢)N_2}{A_w} \qquad (\because a_1 = I/_1¢ \ \& \ a_2 = I/_2¢)$$

$$= \frac{I_1N_1 + I_2N_2}{¢A_w}$$

$$= \frac{2I_1N_1}{¢A_w} \qquad (For\ Ideal\ Transformer\ I_1N_1 = I_2N_2\ )$$

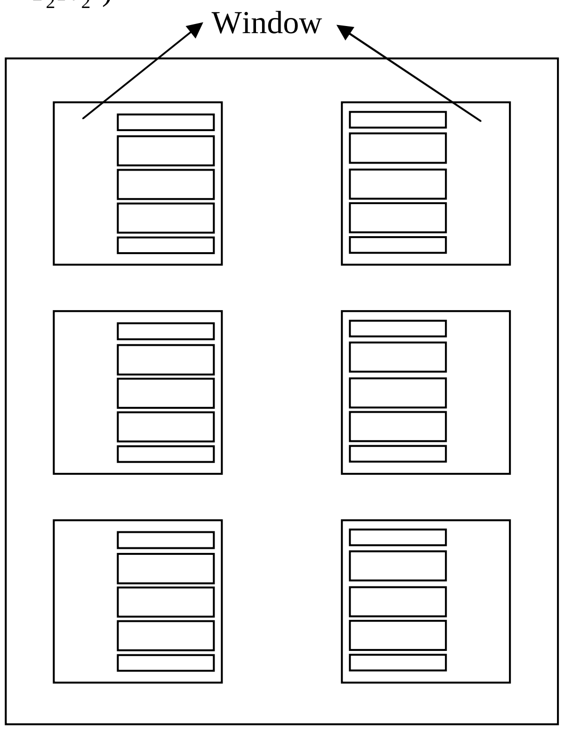
So

$$N_1I_1 = \frac{¢K_wA_w}{2} \quad --------------(9)$$

Put the value of N_1I_1 form equation (9) to equation (6)

$$Q = 3 \times 4.44\ f\ A_i\ B_m \frac{¢\ K_w\ A_w}{2} \times 10^{-3} \qquad KVA$$

$$\boxed{Q = 6.66\ f\ A_i\ B_m\ ¢\ K_w\ A_w \times 10^{-3} \qquad KVA} \quad ---------(10)$$



3-phase shell type transformer with sandwich windings

CHOICE OF MAGNETIC LOADING (B_m)

(1) Normal Si-Steel — 0.9 to 1.1 T
(0.35 mm thickness, 1.5%—3.5% Si)

(2) HRGO — 1.2 to 1.4 T
(Hot Rolled Grain Oriented Si Steel)

(3) CRGO — 1.4 to 1.7 T
(Cold Rolled Grain Oriented Si Steel)
(0.14---0.28 mm thickness)

CHOICE OF ELECTRIC LOADING (¢)

This depends upon cooling method employed

(1) Natural Cooling: 1.5---2.3 A/mm^2

AN	Air Natural cooling
ON	Oil Natural cooling
OFN	Oil Forced circulated with Natural air cooling

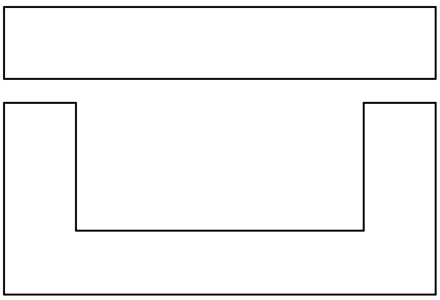
(2) Forced Cooling : 2.2---4.0 A/mm^2

AB	Air Blast cooling
OB	Oil Blast cooling
OFB	Oil Forced circulated with air Blast cooling

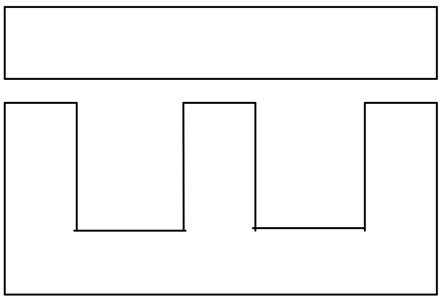
(3) Water Cooling: 5.0 ---6.0 A/mm^2

OW	Oil immersed with circulated Water cooling
OFW	Oil Forced with circulated Water cooling

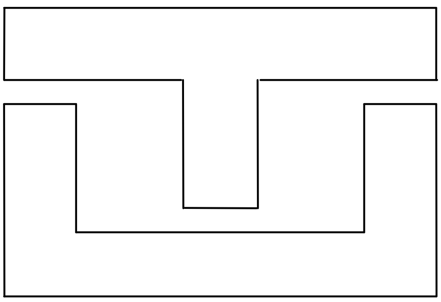
CORE CONSTRUCTION:



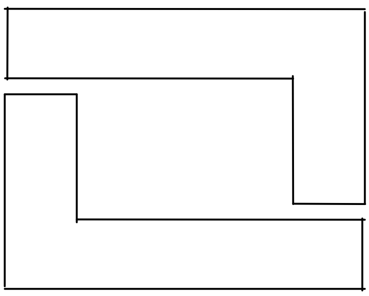
(a) U-I type



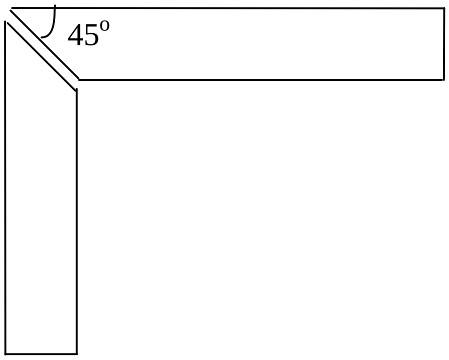
(b) E-I type



(c) U-T type



(d) L-L type



(e) Mitred Core Construction (Latest)

EMF PER TURN:

We know

$$V_1 = 4.44 f\phi_m N_1 \quad \text{--------------(1)}$$

$$So\ EMF/Turn \quad E_t = \frac{V_1}{N_1} = 4.44 f\phi_m \text{-------------(2)}$$

and

$$Q = V_1 I_1 \times 10^{-3} \quad \text{KVA} \qquad (\textbf{Note:}\ \text{Take Q as per phase rating in KVA})$$

$$= (4.44 f\phi_m N_1) I_1 \times 10^{-3} \quad \text{KVA}$$

$$= E_t N_1 I_1 \times 10^{-3} \quad KVA \text{-------(3)}$$

In the design, the ration of total magnetic loading and electric loading may be kept constant

Magnetic loading $= \phi_m$

Electric loading $= N_1 I_1$

So $\frac{\phi_m}{N_1 I_1} = constant\,(say\ "r") \Rightarrow N_1 I_1 = \frac{\phi_m}{r} \quad put\ \ in\ \ eqution(3)$

$$Q = E_t \frac{\phi_m}{r} \times 10^{-3} \quad KVA$$

Or $Q = E_t \frac{E_t}{4.44 f r} \times 10^{-3} \quad KVA$ using equation (2)

$$E_t^2 = (4.44 f r \times 10^{-3}) \times Q$$

Or

$$\boxed{E_t = K_t \sqrt{Q} \qquad Volts/Turn}$$

Where $K_t = \sqrt{4.44 f r \times 10^{-3}}$ is a constant and values are

$K_t =$ 0.6 to 0.7	for 3-phase core type power transformer
$K_t =$ 0.45	for 3-phase core type distribution transformer
$K_t =$ 1.3	for 3-phase shell type transformer
$K_t =$ 0.75 to 0.85	for 1-phase core type transformer
$K_t =$ 1.0 to 1.2	for 1-phase shell type transformer

ESTIMATION OF CORE X-SECTIONAL AREA A_i

We know

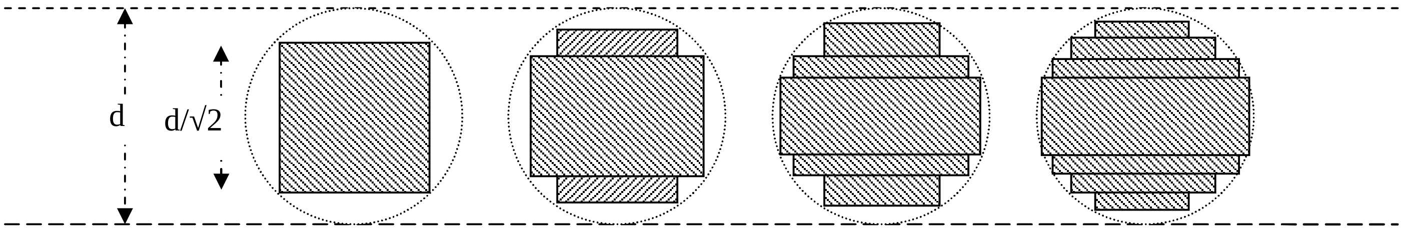
$$E_t = K_t \sqrt{Q} \qquad \text{-----------(1)}$$

$$E_t = 4.44\, f\, ¤_m$$

Or $$E_t = 4.44\, f\, A_i\, B_m \qquad \text{-----------(2)}$$

So $$A_i = \frac{E_t}{4.44\, f\, B_m} \qquad \text{-----------(3)}$$

Now the core may be following types



	1-Step Or Square- Core	2-Step Or Cruciform- Core	3-Step Core	4-Step Core
K=	0.45	0.56	0.60	0.625

d = Diameter of circumscribe circle

For Square core

Gross Area $= \dfrac{d}{\sqrt{2}} \times \dfrac{d}{\sqrt{2}} = 0.5d^2$

Let stacking factor

$$K_i = 0.9$$

Actual Iron Area

$$A_i = 0.9 \times 0.5 d^2$$

$$= 0.45 d^2 \qquad \text{(0.45 for square core and take 'K' as a general case)}$$

$$= K d^2$$

So $$A_i = K d^2$$

Or $$d = \sqrt{\frac{A_i}{K}}$$

Graphical method to calculate dimensions of the core

Consider 2 step core

$$− = \frac{90^o}{n+1}, \qquad n = No\ of\ Steps$$

$i.e\ n = 2$

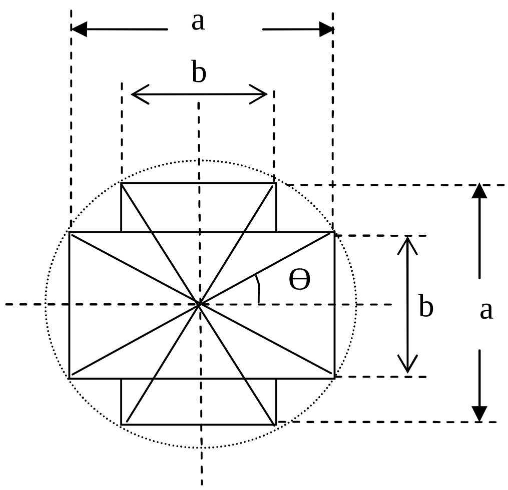
$$− = \frac{90^o}{2+1} = 30^o$$

$So\ \ a = dCos−$

$b = dSin−$

Percentage fill

$$= \frac{Gross\ Area\ of\ Stepped\ core}{Area\ of\ circumcircle} = \frac{Kd^2/K_i}{®d^2/4}$$



2-Step
Or Cruciform- Core

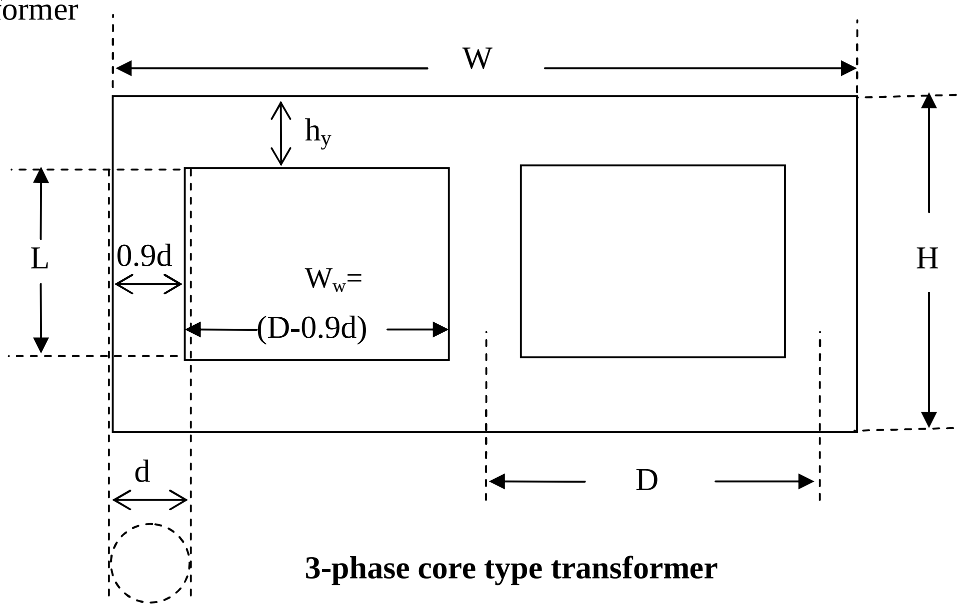
$$= \frac{0.625 d^2 / 0.9}{\frac{\Pi}{4}(d^2)} \qquad \textit{for 4 Step core}$$

$= 0.885$ or 88.5%

No of steps	1	2	3	4	5	6	7	9	11
% Fill	63.7%	79.2%	84.9%	88.5%	90.8%	92.3%	93.4%	94.8%	95.8%

ESTIMATION OF MAIN DIMENSIONS:

Consider a 3-phase core type transformer



3-phase core type transformer

We know output equation

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

So, Window area

$$A_w = \frac{Q}{3.33 f A_i B_m ¢ K_w \times 10^{-3}} \quad m^2$$

where K_w = Window space factor

$$K_w = \frac{8}{30 + HigherKV} \qquad \textit{for upto } 10 \ KVA$$

$$K_w = \frac{10}{30 + HigherKV} \qquad \textit{for upto } 200 \ KVA$$

$$K_w = \frac{12}{30 + HigherKV} \qquad \textit{for upto } 1000 \ KVA$$

For higher rating $K_w = 0.15$ to 0.20

Assume some suitable range for

$D = (1.7 \text{ to } 2)\, d$

Width of the window $W_w = D - 0.9d$

Height of the window

$$L = \frac{A_w}{width\ of\ window(W_w)} \qquad (\because L \times W_w = A_w)$$

Generally $\frac{L}{W_w} = 2 \ to \ 4$

The yoke can have same area as that of the core and can be of same stepped size as core (in this case D_y=a, h_y=a). Alternatively it could be of rectangular section. In that case yoke area A_y is generally taken 10% to 15% higher then core section area (A_i), it is to reduce the iron loss in the yoke section. But if we increase the core section area (A_i) more copper will be needed in the windings and so more cost through we are reducing the iron loss in the core. Further length of the winding will increase, resulting higher resistance so more cu loss.

$A_y = (1.10 \text{ to } 1.15) A_i$

Depth of yoke $D_y = a$

Height of the yoke $h_y = A_y/D_y$

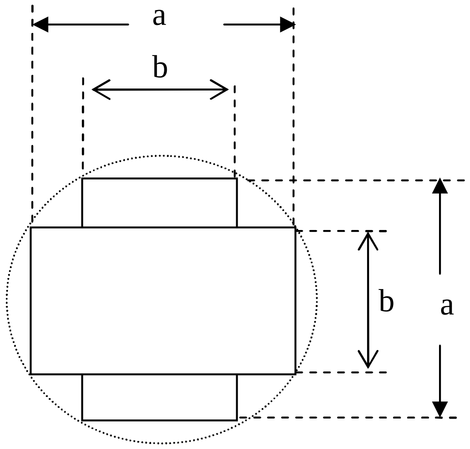
Width of the core

$W = 2*D + 0.9\ d$

Or $W = 2W_w + 3x0.9d$ (As $W_w = D - 0.9d$)

Height of the core

$H = L + 2*h_y$



2-Step
Or Cruciform- Core

Flux density in yoke

$$B_y = \frac{A_i}{A_y} B_m$$

ESTIMATION OF CORE LOSS AND CORE LOSS COMPONET OF NO LOAD CURRENT I_C:

Volume of iron in core $= 3*L*A_i$ m^3

Weight of iron in core = density * volume

$= \circ_i * 3*L*A_i$ Kg

$\circ_i$ = density of iron (kg/m^3)

$=7600\ Kg/m^3$ for normal Iron/steel

$= 6500\ Kg/m^3$ for M-4 steel

From the graph we can find out specific iron loss, p_{core} (Watt/Kg) corresponding to flux density B_m in core.

So

Iron loss in core $= p_{core} * \circ_i * 3*L*A_i$ Watt

Similarly

Iron loss in yoke $= p_{yoke} * \circ_i * 2*W*A_y$ Watt

Where p_{yoke} = specific iron loss corresponding to flux density B_y in yoke

Total Iron loss P_i = Iron loss in core + Iron loss in yoke

Core loss component of no load current

I_c = Core loss per phase/ Primary Voltage

$$I_c = \frac{P_i}{3V_1}$$

ESTIMATION OF MAGNETIZING CURRENT OF NO LOAD CURRENT I_m:

Find out magnetizing force H (at_{core}, at/m) corresponding to flux density B_m in the core and at_{yoke} corresponding to flux density in the yoke from B-H curve

$$\left(B_m \Rightarrow at_{core}/m, \quad B_c \Rightarrow at_{yoke}/m \right)$$

So

MMF required for the core = $3*L*at_{core}$

MMF required for the yoke = $2*W*at_{yoke}$

We account 5% AT for joints etc

So total MMF required = 1.05[MMF for core + MMF for yoke]

Peak value of the magnetizing current

$$I_{m,\,peak} = \frac{Total\ MMF\ required}{3N_1}$$

RMS value of the magnetizing current

$$I_{m,\,RMS} = \frac{I_{m,\,peak}}{\sqrt{2}}$$

$$I_{m,\,RMS} = \frac{Total\ MMF\ required}{3\sqrt{2}N_1}$$

ESTITMATION OF NO LOAD CURRENT AND PHASOR DIAGRAM:

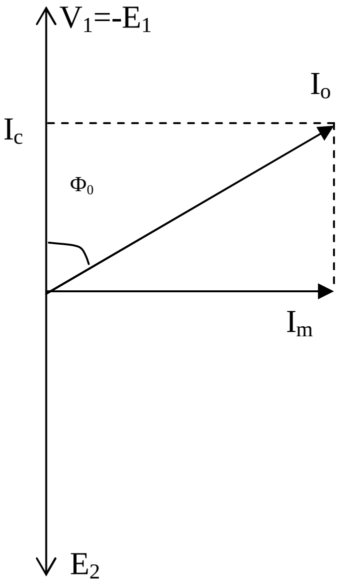
No load current Io

$$I_o = \sqrt{I_c^{\ 2} + I_m^{\ 2}}$$

No load power factor

$$Cos¤_o = \frac{I_c}{I_o}$$

The no load current should not exceed 5% of the full load current.



No load phasor diagram

ESTIMATION OF NO OF TURNS ON LV AND HV WINDING

Primary no of turns $N_1 = \frac{V_1}{E_t}$

Secondary no of turns $N_2 = \frac{V_2}{E_t}$

ESTIMATION OF SECTIONAL AREA OF PRIMARY AND SECONDARY CONDUCTORS

Primary current $I_1 = \dfrac{Q \times 10^{-3}}{3V_1}$

Secondary current $I_2 = \dfrac{Q \times 10^{-3}}{3V_2} \quad OR \quad \dfrac{N_1}{N_2} I_1$

Sectional area of primary conductor $a_1 = \dfrac{I_1}{¢}$

Sectional area of secondary conductor $a_2 = \dfrac{I_2}{¢}$

Where ¢ is current the density.

Now we can use round conductors or strip conductors for this see the IS codes and ICC (Indian Cable Company) table.

DETERMINATION OF R_1 & R_2 AND CU LOSSES:

Let L_{mt} = Length of mean turn

Resistance of primary winding

$$R_{1,\ dc,\ 75^o} = 0.021 \times 10^{-6} \frac{L_{mt} N_1 (m)}{a_1 (m^2)}$$

$$R_{1,\ ac,\ 75^o} = (1.15 \ \ to \ \ 1.20) R_{1,\ dc,\ 75^o}$$

Resistance of secondary winding

$$R_{2,\ dc,\ 75^o} = 0.021 \times 10^{-6} \frac{L_{mt} N_2 (m)}{a_2 (m^2)}$$

$$R_{2,\ ac,\ 75^o} = (1.15 \ \ to \ \ 1.20) R_{2,\ dc,\ 75^o}$$

Copper loss in primary winding $= 3I_1^2 R_1 \quad Watt$

Copper loss in secondary winding $= 3I_2^2 R_2 \quad Watt$

Total copper loss $= 3I_1^2 R_1 + 3I_2^2 R_2$

$= 3I_1^2 (R_1 + R_2')$

$= 3I_1^2 R_p$

Where $R_{01} = R_p = R_1 + R_2'$

$= Total$ resistance $referred \ \ to \ \ primary \ \ side$

Note: Even at no load, there is magnetic field around connecting leads, tanks etc which causes additional stray losses in the transformer tanks and other metallic parts. These losses may be taken as 7% to 10% of total cu losses.

DETERMINATION OF EFFICIENCY:

Efficiency ¦ $= \dfrac{Output \ \ Power}{Input \ \ Power}$

¦ $= \dfrac{Output \ \ Power}{Output \ \ Power + Losses}$

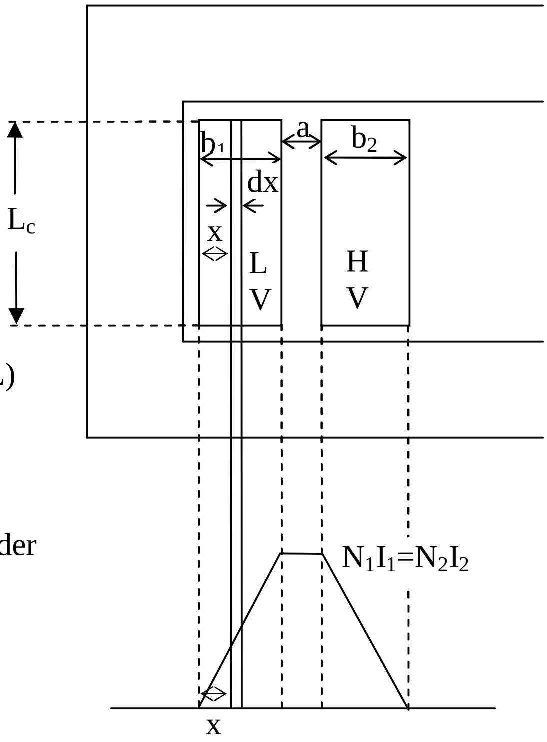
¦ $= \dfrac{Output \ \ Power}{Output \ \ Power + Iron \ \ Loss \ + Cu \ \ loss} \times 100 \ \%$

ESTIMATION OF LEAKAGE REACTANCES(X_1 & X_2):

Assumptions

1. Consider permeability of iron as infinity that is MMF is needed only for leakage flux path in the window.
2. The leakage flux lines are parallel to the axis of the core.

Consider an elementary cylinder of leakage flux lines of thickness 'dx' at a distance x as shown in following figure.



MMF Distribution

MMF at distance x

$$M_x = \frac{N_1 I_1}{b_1} x$$

Permeance of this elementary cylinder

$$= \mu_o \frac{A}{L}$$

$$= \mu_o \frac{L_{mt} dx}{L_c} \quad (L_c = \text{Length of winding} \approx 0.8L)$$

$$\left(\because S = \frac{1}{\mu_o}\frac{L}{A} \quad \& \quad Permeance = \frac{1}{S} \right)$$

Leakage flux lines associated with elementary cylinder

$$d\phi_x = M_x \times Permeance$$

$$= \frac{N_1 I_1}{b_1} x \times \mu_o \frac{L_{mt} dx}{L_c}$$

Flux linkage due to this leakage flux

$$d\psi_x = No\ of\ \ truns\ with\ which\ it\ is\ associated \times d\phi_x$$

$$= \frac{N_1 I_1}{b_1} \times \frac{N_1 I_1}{b_1} x \times \mu_o \frac{L_{mt} dx}{L_c}$$

$$= \mu_o N_1^2 \frac{L_{mt}}{L_c} I_1 \left(\frac{x}{b_1} \right)^2 dx$$

Flux linkages (or associated) with primary winding

$$\psi_1' = \mu_o N_1^2 \frac{L_{mt}}{L_c} I_1 \int_0^{b_1} \left(\frac{x}{b_1} \right)^2 dx = \mu_o N_1^2 \frac{L_{mt}}{L_c} I_1 \left(\frac{b_1}{3} \right)$$

Flux linkages (or associated) with the space 'a' between primary and secondary windings

$$\psi_o = \mu_o N_1^2 \frac{L_{mt}}{L_c} I_1 a$$

We consider half of this flux linkage with primary and rest half with the secondary winding. So total flux linkages with primary winding

$$\psi_1 = \psi_1' + \frac{\psi_o}{2}$$

$$\psi_1 = \mu_o N_1^2 \frac{L_{mt}}{L_c} I_1 \left(\frac{b_1}{3} + \frac{a}{2} \right)$$

Similarly total flux linkages with secondary winding

$$\phi_2 = \phi_2' + \frac{\phi_o}{2}$$

$$\phi_2 = \mu_o N_2^2 \frac{L_{mt}}{L_c} I_2 \left(\frac{b_2}{3} + \frac{a}{2}\right)$$

Primary & Secondary leakage inductance

$$L_1 = \frac{\phi_1}{I_1} = \mu_o N_1^2 \frac{L_{mt}}{L_c} \left(\frac{b_1}{3} + \frac{a}{2}\right)$$

$$L_2 = \frac{\phi_2}{I_2} = \mu_o N_2^2 \frac{L_{mt}}{L_c} \left(\frac{b_2}{3} + \frac{a}{2}\right)$$

Primary & Secondary leakage reactance

$$X_1 = 2\Pi f L_1 = 2\Pi f \mu_o N_1^2 \frac{L_{mt}}{L_c} \left(\frac{b_1}{3} + \frac{a}{2}\right)$$

$$X_2 = 2\Pi f L_2 = 2\Pi f \mu_o N_2^2 \frac{L_{mt}}{L_c} \left(\frac{b_2}{3} + \frac{a}{2}\right)$$

Total Leakage reactance referred to primary side

$$X_{01} = X_P = X_1 + X_2' = 2\Pi f \mu_o N_1^2 \frac{L_{mt}}{L_c} \left(\frac{b_1 + b_2}{3} + a\right)$$

Total Leakage reactance referred to secondary side

$$X_{02} = X_S = X_1' + X_2 = 2\Pi f \mu_o N_2^2 \frac{L_{mt}}{L_c} \left(\frac{b_1 + b_2}{3} + a\right)$$

It must be 5% to 8% or maximum 10%

Note:- How to control X_P?

If increasing the window height (L), L_c will increase and following will decrease b_1, b_2 & L_{mt} and so we can reduce the value of X_P.

CALCULATION OF VOLTAGE REGULATION OF TRANSFORMER:

$$V.R. = \frac{I_2 R_{o2} Cos\phi_2 \pm I_2 X_{o2} Sin\phi_2}{E_2} \times 100$$

$$= \frac{R_{o2} Cos\phi_2}{E_2 / I_2} \times 100 \pm \frac{X_{o2} Sin\phi_2}{E_2 / I_2} \times 100$$

$$= \%R_{o2} Cos\phi_2 \pm \%X_{o2} Sin\phi_2$$

TRANSFORMER TANK DESIGN:

Width of the transformer (Tank)

$W_t = 2D + D_e + 2b$

Where D_e= External diameter of HV winding

b = Clearance width wise between HV and tank

Depth of transformer (Tank)

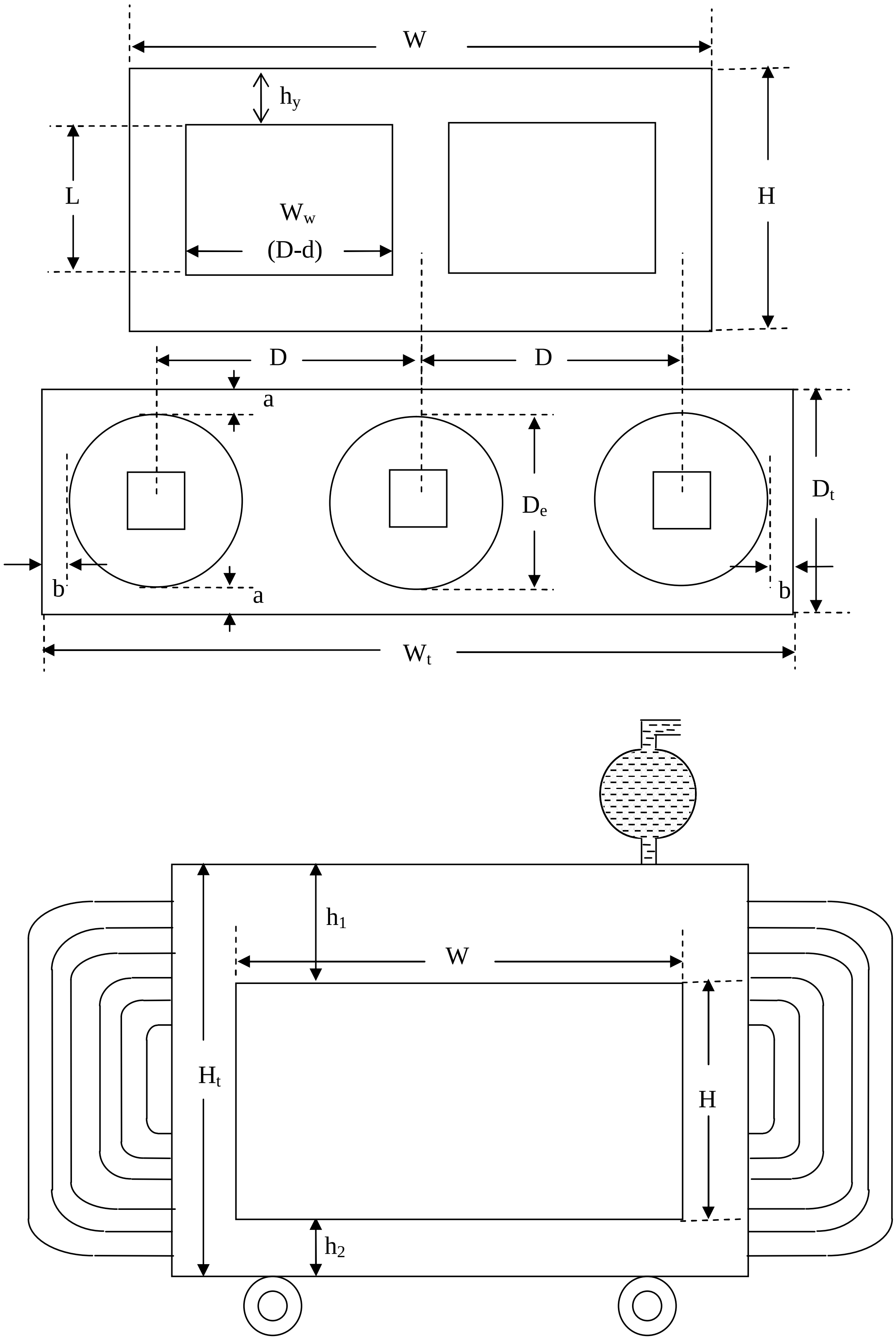
$D_t = D_e + 2a$

Where a= Clearance depth wise between HV and tank

Height of transformer (Tank)

$H_t = H + h$

Where $h = h_1 + h_2$= Clearance height wise of top and bottom



Tank of a 3-Phase transformer

CALCULATION OF TEMPERATURE RISE:

Surface area of 4 vertical side of the tank (Heat is considered to be dissipated from 4 vertical sides of the tank)

$S_t = 2(W_t + D_t)\, H_t$ m^2 (Excluding area of top and bottom of tank)

Let

– = Temp rise of oil (35° C to 50° C)

$12.5 S_t$ – =Total full load losses (Iron loss + Cu loss)

So temp rise in °C – = $\dfrac{\text{Total full load losses}}{12.5\ S_t}$

If the temp rise so calculated exceeds the limiting value, a suitable no of cooling tubes or radiators must be provided

CALCULATION OF NO OF COOLING TUBES:

Specific Heat dissipation
6 Watt/m^2-^{0}C by Radiation
6.5 Watt/m^2-^{0}C by Convection

Let xS_t= Surface area of all cooling tubes

Then

Losses to be dissipated by the transformer walls and cooling tube

= Total losses

$(12.5 S_t + 8.5 xS_t)$ – = Total losses

6 W-Raditon+6.5 W-Convection=12.5

6.5*1.35 W ≈ 8.5 (≈35% more) Convection only

So from above equation we can find out total surface area of cooling tubes (xS_t)

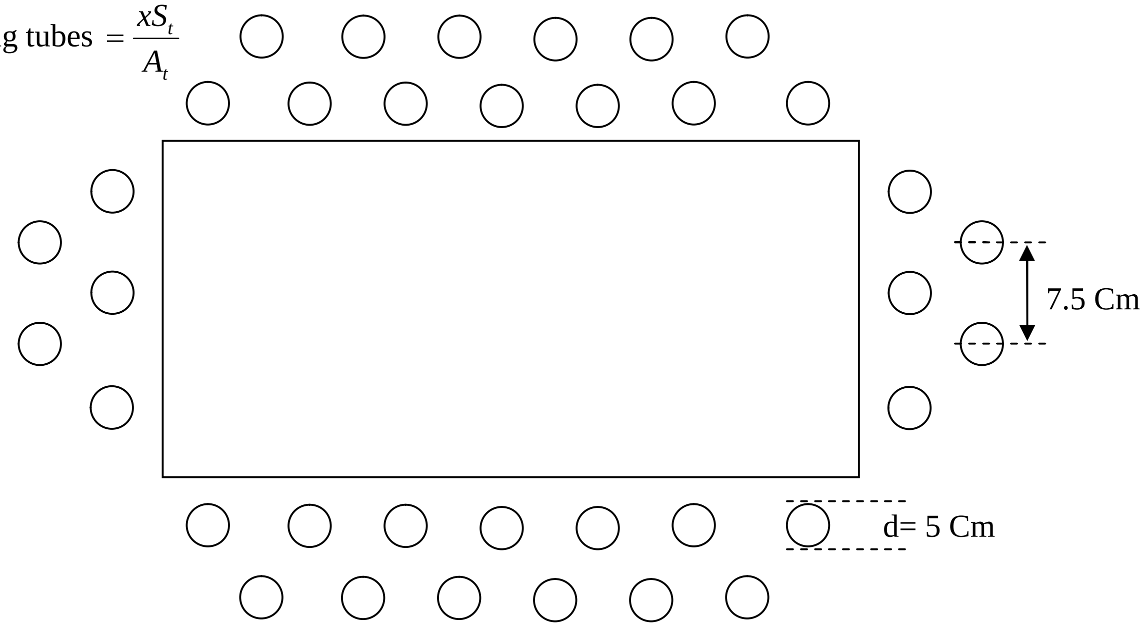
Normally we use 5 cm diameter tubes and keep them 7.5 cm apart

A_t= Surface area of one cooling tube

= ®$d_{tube} l_{tube,\ mean}$

Hence

No of cooling tubes $= \dfrac{xS_t}{A_t}$



Tank and Arrangement of Cooling tubes

WEIGHT OF TRANFORMER:

Let

W_i = Weight of Iron in core and yoke (core volume* density + yoke volume* density) Kg
W_c= Weight of copper in winding (volume* density) Kg
(density of cu = 8900 Kg/m^3)
Weight of Oil
= Volume of oil * 880 Kg
Add 20% of (W_i+W_c) for fittings, tank etc.
Total weight is equal to weight of above all parts.

Example 1: Estimate the main core dimensions for a 50 Hz, 3-phase, 200 KVA, 6600/500 V, Star/mesh connected core type transformer. Use the following data:
Core limb section to be 4-stepped for which the area factor =0.62
Window space factor =0.27

$$\frac{Height\ \ of\ \ window}{Width\ \ of\ \ window} = 2$$

Current density = 2.8 MA/m^2
Volts per turn =8.5
Maximum flux density =1.25 Wb/m^2.

Solution:
We know emf per turn

$$E_t = 4.44 fA_i B_m \Rightarrow \quad 8.5 = 4.44 \times 50 \times A_i \times 1.25$$

$\Rightarrow Ai=0.03063\ m^2$

For 4 stepped core

$$A_i = K\ d^2 \quad \Rightarrow \quad 0.03063 = 0.625\ d^2$$

$\Rightarrow d = 0.2214$ m

We also know

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

$$\Rightarrow 200 = 3.33 \times 50 \times 0.03063 \times 1.25 \times 2.8 \times 10^6 \times 0.27\ A_w \times 10^{-3}$$

$\Rightarrow A_w = 0.0415\ m^2 = L x W_w$ ---------- (1)

$\frac{L}{W_w} = 2$ ---------- (2)

Solving (1) & (2)

W_w = 0.144 m

L = 0.288 m

Ay =1.15 Ai (Let yoke area Ay is 15% more than area Ai)
D_y= a (Width of largest stamping)
=d CosΘ

D_y=0.92 d (To give maximum area Ai)
Or =0.95 d (By Graphical Method)

Selecting D_y =0.92 d

$\Rightarrow D_y$=0.204 m

Also assuming rectangular section for yoke
$h_y = A_y/D_y = 1.15A_i/D_y$ (Assuming Ay=15% more than A_i)
=1.15x0.03063/0.204

$\Rightarrow h_y$=0.173 m

Overall height H=L+h_y =0.288+0.173 $\Rightarrow$ H=0.461 m

Overall width W= 2D+0.9d = 2Ww+3x0.9d=2x0.144+3x0.9x0.2214

$\Rightarrow$ W=0.88578 m

Example 2: Calculate no load current of a 400 V, 50 Hz, 1-Phase, core type transformer, the particulars of which are as follows:
Length of means magnetic path =200 Cm,
Gross core section =100 Cm^2,
Joints equivalent to 0.1 mm air gap,
Maximum flux density =0.7 T,
Specific core loss at 50 Hz & 0.7 T =0.5 W/Kg,
Ampere turns =2.2 per cm for 0.7 T,
Stacking factor =0.9,
Density of core material = 7.5x 10^3 Kg/m^3.

Solution:

<u>Find I_C:</u>

$$Core\ loss\ component\ of\ no\ load\ current\ I_C = \frac{Totol\ core\ loss}{V_1} = \frac{Specific\ core\ loss \times Weight\ of\ core}{V_1}$$

$$I_C = \frac{Specific\ core\ loss \times \left(K_i \times A_{gi} \times length \times density\right)}{V_1} = \frac{0.5 \times 0.9 \times 100 \times 10^{-4} \times 200 \times 10^{-2} \times 7.5 \times 10^3}{400}$$

$\Rightarrow$ I_C=0.168 A

<u>Find I_m:</u>

We know $V1 = 4.44\, f A_i B_m N_1$

$400 = 4.44 \times 50 \times 0.9 \times 100 \times 10^{-4} \times 0.7 \times N_1 \Rightarrow$ N_1=286

$$Magnetizing\ component\ I_m = \frac{Totol\ MMF}{\sqrt{2}\, N_1} = \frac{MMF\ \ for\ core + MMF\ for\ airgap\ of\ length\ of\ 0.1mm}{\sqrt{2}\, N_1}$$

$$I_m = \frac{MMF\ \ for\ core + B_m \times \frac{1}{\mu_0} l_g}{\sqrt{2}\, N_1} = \frac{2.2 \times 200 + 0.7 \times \frac{1}{4\pi \times 10^{-7}} \times 0.1 \times 10^{-3}}{\sqrt{2} \times 286} \qquad \left(\because MMF = \phi \times S = B_m \times \frac{1}{\mu_0} l_g\right)$$

$\Rightarrow$ I_m=1.226 A

So No load current

$$I_0 = \sqrt{I_C^2 + I_m^2} = \sqrt{0.168^2 + 1.226^2}$$

$\Rightarrow$ I_0=1.237 A

Example 3: Design an adequate cooling arrangement for a 250 KVA, 6600/400 V, 50 Hz, 3-phase, delta/star core type oil immersed natural cooled transformer with the following particulars:
Winding temperature rise not to exceed 50^0 C,
Total losses at 90^0 C are 5 Kw,
Tank Dimensions height x length x width = 125 x 100 x 50 (all in cm)
Oil level = 115 cm length
Sketch diagram to show the arrangement of cooling tubes.

Solution:

Dissipating surface area of plain tank after neglecting the top and bottom

S_t=2(W_t+D_t)H_t=2(50+100)125=3.75x10^4 cm^2=3.75 m^2

$$- = \frac{\text{Total full load losses}}{12.5\ S_t} = \frac{5000}{12.5 \times 3.75} = 106.66^0\ C$$

But it is required that the temp rise is not to exceed 50^0 C. So cooling tubes are required.

Let xSt = Surface area of all cooling tubes

$$\left(12.5S_t + 8.5xS_t\right)\overline{\ } = \text{Total losses}$$

⇒ $xSt = 6.25\ m^2$

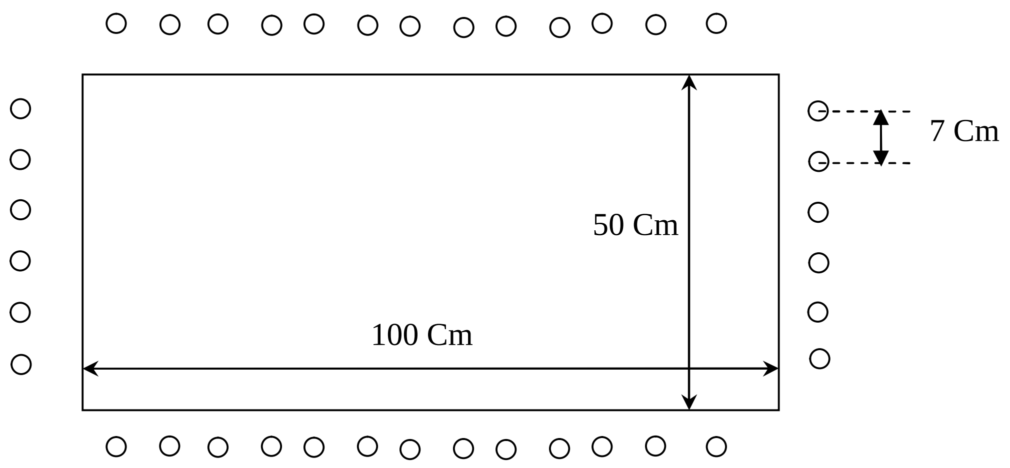
Surface area of one cooling tube (Assuming Tube dia = 5 cm, average height of tube =105 cm)

$$A_t = \text{®} d_{tube} l_{tube,\ mean} = 3.14 \times 0.05 \times 1.05 = 0.1649\, m^2$$

$$\text{No of cooling tubes} = \frac{xS_t}{A_t} = \frac{6.25}{0.1649} \approx 38$$

Let the tubes to space 7 cm apart centre to centre, we will be able to accommodate 13 tubes on 100 cm side and 6 tubes on 50 cm side.

Total tubes =2x13+2x6=38



Tank and Arrangement of Cooling tubes