Unit 2

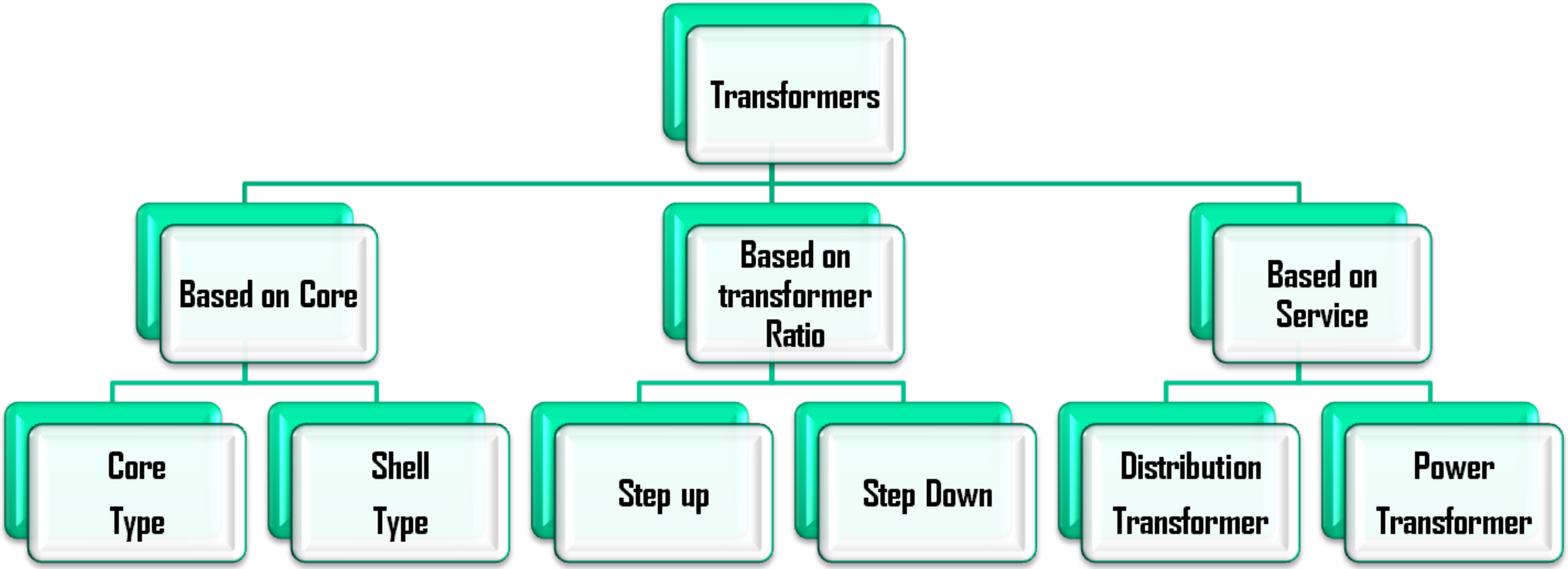
Design of Three Phase and Single Phase Transformer

Introduction

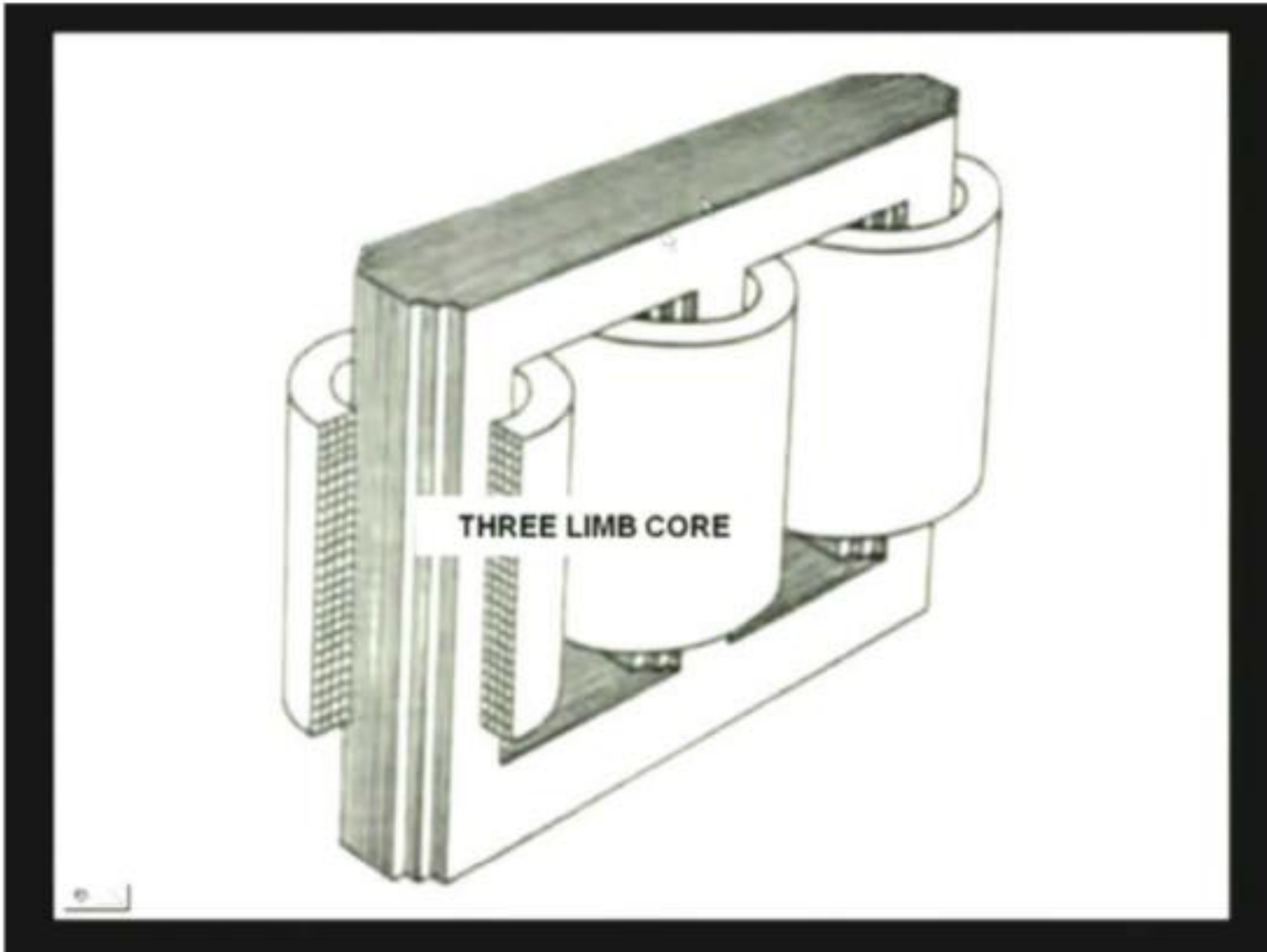
Constituents of transformer:

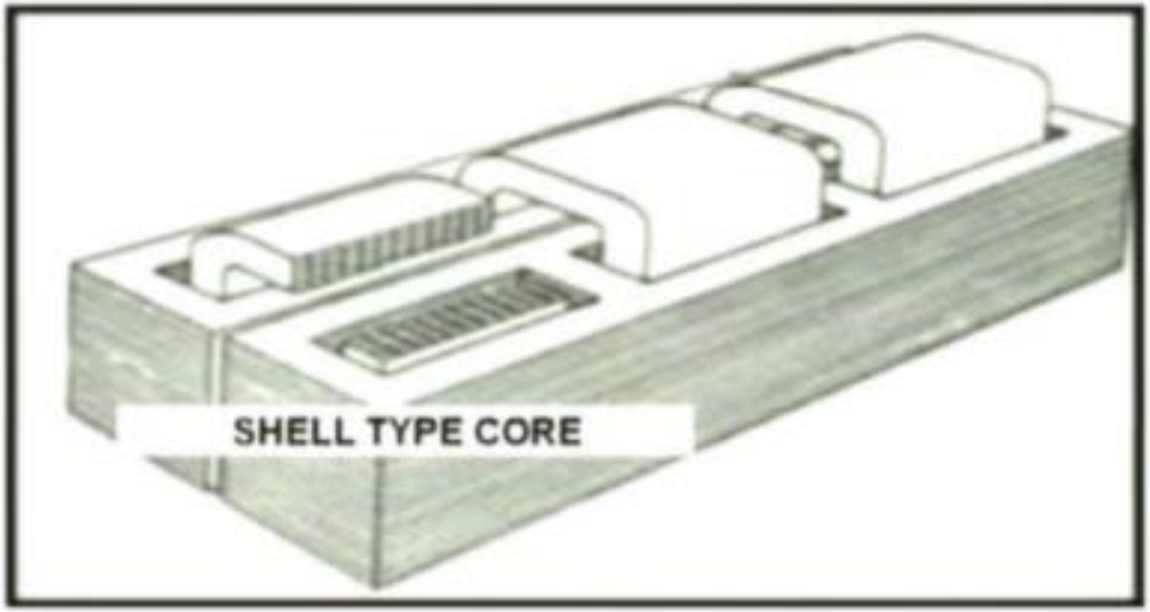
i. Magnetic Circuit
ii. Electric Circuit
iii. Dielectric Circuit
iv. Other accessories

Classification or Types



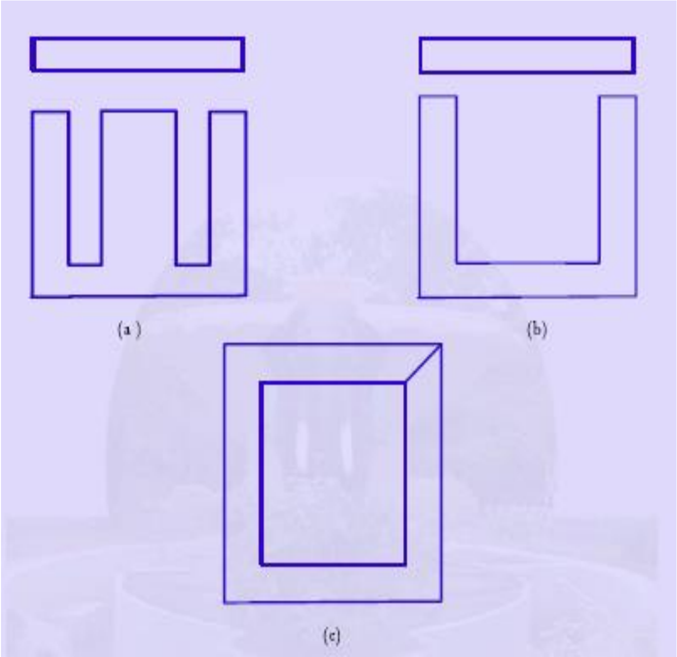
Constructional Details


THREE LIMB CORE


SHELL TYPE CORE

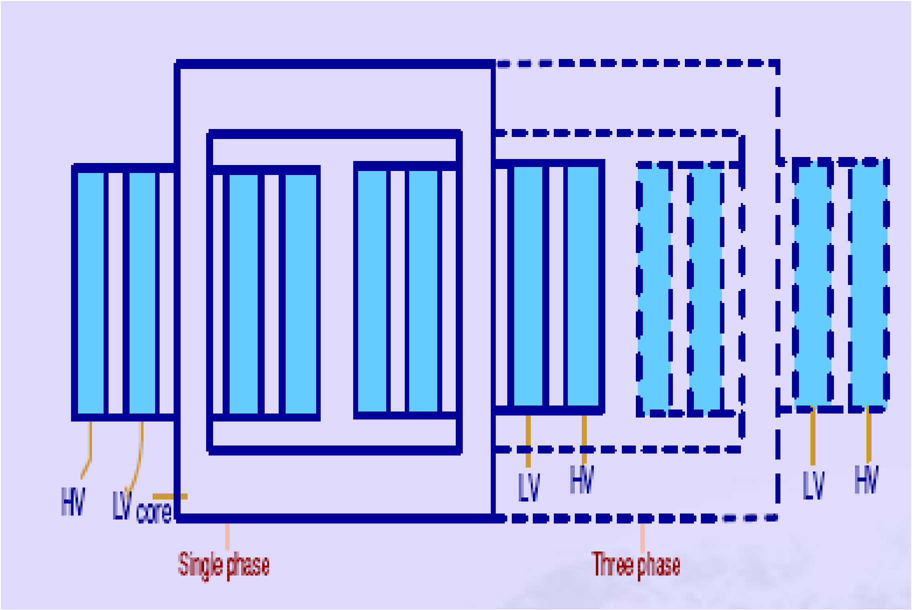
Constructional Details

- The requirements of magnetic material are,
  - **High permeability**
  - **Low reluctance**
  - **High saturation flux density**
  - **Smaller area under B-H curve**
- For small transformers, the laminations are in the form of E,I, C and O as shown in figure
- The percentage of silicon in the steel is about 3.5. Above this value the steel becomes very brittle and also very hard to cut

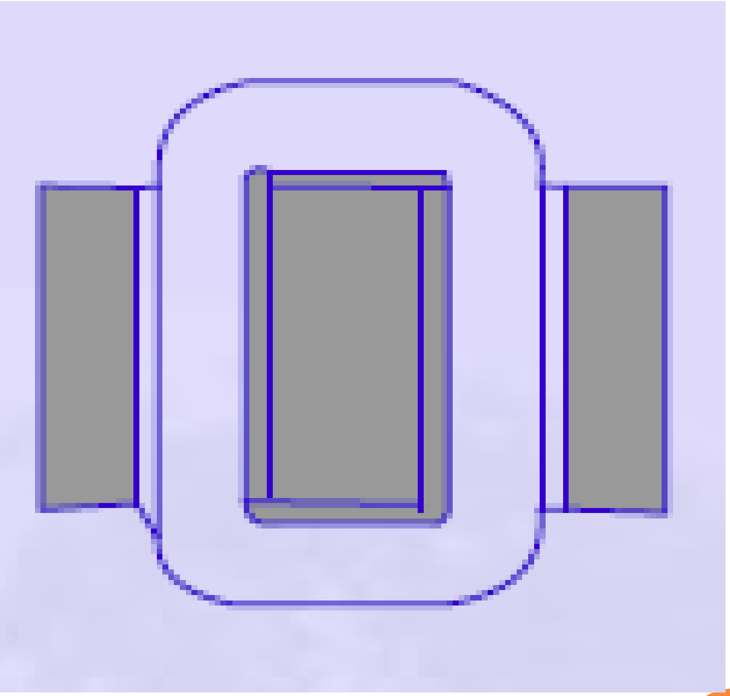


Transformer Core

Core type Construction



Shell Type Construction



Output Equation of Transformer

- It relates the rated kVA output to the area of core & window
- The output kVA of a transformer depends on,
  - Flux Density (B) – related to Core area
  - Ampere Turns (AT) – related to Window area
- Window – Space inside the core – to accommodate primary & secondary winding

Let,

T- No. of turns in transformer winding

f – Frequency of supply

Induced EMF/Turn , $E_t = E/T = 4.44 f \varphi_m$

Output Equation of Transformer

- Window in a 1φ transformer contains one primary & one secondary winding.

$$\text{Window Space factor,} K_w = \frac{\text{Conductor area in Window}}{\text{Total area of Window}}$$

$$\text{Window Space factor,} K_w = \frac{A_c}{A_w}$$

$$\therefore \text{Conductor area in window, } A_c = K_w A_w \rightarrow (2)$$

Current Density (δ) *is same in both the windings*

$$\delta = \frac{I_p}{a_p} = \frac{I_s}{a_s} \rightarrow (3)$$

Output Equation of Transformer

$$\therefore a_p = \frac{I_p}{\delta} \;;\; a_s = \frac{I_s}{\delta}$$

If we neglect magnetizing MMF, then $(AT)_{primary} = (AT)_{secondary}$

$$\therefore AT = I_p T_p = I_s T_s \rightarrow (4)$$

Total Cu. Area in window, Ac=Cu.area of pry wdg + Cu.area of sec wdg

$$= T_p\, a_p + T_s\, a_s$$

$$T_p\, a_p + T_s\, a_s$$

$$T_p \frac{I_p}{\delta} + T_s \frac{I_s}{\delta}$$

$$\frac{1}{\delta}\left[T_p I_p + T_s I_s\right]$$

$$\frac{1}{\delta}\left[AT + AT\right] = \frac{2AT}{\delta} \rightarrow (5)$$

Output Equation of Transformer

Therefore, equating (2) & (5),

$$K_w A_w = \frac{2\,AT}{\delta}$$

$$AT = \frac{1}{2} K_w A_w \delta \rightarrow (6)$$

kVA rating of 1φ transformer is given by,

$$Q = V_p I_p \times 10^{-3} \approx E_p I_p \times 10^{-3}$$

$$= \frac{E_p}{T_p} T_p I_p \times 10^{-3} \quad \left[from\ (1),\ E_t = \frac{E}{T} \right]$$

$$= E_t \, AT \times 10^{-3} \rightarrow (6)$$

$$= 4.44 f \varphi_m . \frac{1}{2} K_w A_w \delta \times 10^{-3}$$

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

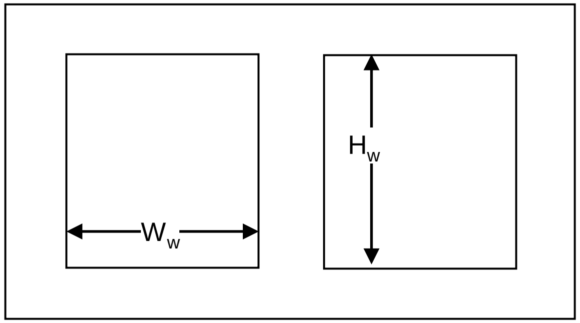
Output Equation of Transformer

We know that, $B_m = \dfrac{\varphi_m}{A_i}$ *and* $\varphi_m = B_m A_i$

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

Three phase transformer:

- Each window has 2 primary & 2 Secondary windings.
- Total Cu. Area in the window is given by,



$$A_c = 2T_p\, a_p + 2\,T_s\, a_s$$

$$A_c = \frac{4\,AT}{\delta} \rightarrow (7)$$

$$Compare\ (2) \wedge (7), \Rightarrow \frac{4\,AT}{\delta} = K_w\, A_w$$

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

Output Equation of Transformer

kVA rating of 3φ transformer,

$$Q = 3\ E_p I_p \times 10^{-3}$$

$$= 3 \frac{E_p}{T_p} T_p I_p \times 10^{-3}$$

$$= E_t \square AT \times 10^{-3}$$

$$= 3 \times 4.44 \times f\varphi_m . \times \frac{1}{4} K_w A_w \delta \times 10^{-3}$$

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

EMF per Turn

- Design of Xmer starts with the section of EMF/turn.

Let, Ratio of Specific magnetic loading to Electric loading

$$\{\ \}\{\ \}r = \frac{\varphi_m}{AT}$$

$$Q = V_p I_p \times 10^{-3}$$

$$= 4.44\ f\ \varphi_m\ T_p I_p \times 10^{-3}$$

$$= 4.44\ f\ \varphi_m\ (AT) \times 10^{-3}$$

$$= 4.44\ f\ \varphi_m\ \frac{\varphi_m}{r} \times 10^{-3}$$

$$\varphi_m^2 = \frac{Q \cdot r}{4.44\ f \times 10^{-3}} = \frac{Q \cdot r \times 10^3}{4.44\ f}$$

$$\varphi_m = \sqrt{\frac{Q \cdot r \times 10^3}{4.44\ f}}$$

EMF per Turn

$$w.k.t,\ E_t = 4.44\, f\, \varphi_m$$

$$= 4.44\, f \sqrt{\frac{Q \cdot r \times 10^3}{4.44\, f}} = \sqrt{4.44\, f} \cdot \sqrt{4.44\, f} \cdot \sqrt{r \times 10^3} . \frac{\sqrt{Q}}{\sqrt{4.44\, f}}$$

$$= \sqrt{4.44\, f \cdot r \times 10^3} \cdot \sqrt{Q}$$

$$where,\ K = \sqrt{4.44\, f \cdot r \times 10^3} \qquad E_t = K \cdot \sqrt{Q}$$

- K depends on the type, service condition & method of construction of transformer.

EMF per Turn

Transformer Type	Value of K
1φ Shell Type	1.0 to 1.2
1φ Core Type	0.75 to 0.85
3φ Shell Type	1.2 to 1.3
3φ Core Type Distribution transformer	0.45 to 0.5
3φ Core Type Power transformer	0.6 to 0.7

Optimum Design

- Transformer may be designed to make one of the following quantities as minimum.
  - Total Volume
  - Total Weight
  - Total Cost
  - Total Losses
- In general, these requirements are contradictory & it is normally possible to satisfy only one of them.
- All these quantities vary with $r = \frac{\varphi_m}{AT}$

Optimum Design

Design for Minimum Cost

Let us consider a single phase transformer.

$$Q = 2.22 \cdot f\, B_m\, A_i\, A_w\, K_w \delta \times 10^{-3} \quad kVA$$

$$Q = 2.22 \cdot f\, B_m\, A_i\, A_c \delta \times 10^{-3} \quad kVA \quad [A_c = K_w A_w]$$

Assuming that flux & current densities are constant, $A_c.A_i$ – Constant

$$A_c\, A_i = M^2 \rightarrow (1)$$

Let,In optimum design, it aims to determining the minimum value of total cost.

$$r = \frac{\varphi_m}{AT}$$

$$\varphi_m = B_m A_i$$

$$AT = \frac{1}{2} K_w A_w \delta = \frac{A_c \delta}{2}$$

Optimum Design

Design for Minimum Cost

Let, C_t - Total cost of transformer active materials

C_i – Cost of iron

C_c – Cost of conductor

p_i – Loss in iron/kg (W)

p_c – Loss in Copper/kg (W)

l_i – Mean length of flux path in iron(m)

L_{mt} – Mean length of turn of transformer winding (m)

G_i – Weight of active iron (kg)

G_c – Weight of Copper (kg)

g_i – Weight/m^3 of iron

g_c – Weight/m^3 of Copper

$$C_t = C_i + C_c = c_i G_i + c_c G_c$$

Optimum Design

Design for Minimum Cost

$$r = \frac{B_m A_i}{\frac{A_c \delta}{2}} = \frac{2\ B_m A_i}{A_c \delta}$$

$$r = \frac{A_i}{A_c} \frac{2\ B_m}{\delta}$$

$$\frac{A_i}{A_c} = \frac{\delta}{2\ B_m} \cdot r = \beta \quad \rightarrow (2)$$

β is the function of r alone [δ & B_m – Constant]

From (1) & (2),

$$A_i = M\sqrt{\beta} \quad \wedge A_c = \frac{M}{\sqrt{\beta}} \qquad [\because A_c A_i = M^2]$$

Optimum Design

Design for Minimum Loss and Maximum Efficiency

Total losses at full load = $P_i + P_c$

At any fraction x of full load, total losses = $P_i + x^2 P_c$

If output at a fraction of x of full load is xQ.

Efficiency, $$\eta_x = \frac{\mathbf{xQ}}{\mathbf{xQ} + P_i + x^2 P_c}$$

Condition for maximum efficiency is, $$\frac{d\eta_x}{dx} = 0$$

$$\frac{d\eta_x}{dx} = \frac{\left(\mathbf{xQ} + P_i + x^2 P_c\right)\mathbf{Q} - \left(Q + \mathbf{2xP}_c\right)\mathbf{xQ}}{\left(\mathbf{xQ} + P_i + x^2 P_c\right)^2} = 0$$

$$\left(\mathbf{xQ} + P_i + x^2 P_c\right)Q = \left(Q + \mathbf{2xP}_c\right)\mathbf{xQ}$$

$$\left(\mathbf{xQ} + P_i + x^2 P_c\right) = \left(Q + \mathbf{2xP}_c\right)x$$

$$\mathbf{xQ} + P_i + x^2 P_c = \mathbf{xQ} + x^2 P_c + x^2 P_c$$

$$P_i = x^2 P_c$$

Optimum Design

Design for Minimum Cost

$$C_t = c_i g_i l_i A_i + c_c g_c L_{\mathrm{mt}} A_c$$

where. c_i ∧ c_c − *specific costs of iron and copper respectively.*

$$C_t = c_i g_i l_i M\sqrt{\beta} + c_c g_c L_{\mathrm{mt}} \frac{M}{\sqrt{\beta}}$$

Differentiating C_t with respect to β,

$$\frac{d}{d\beta} C_t = \frac{1}{2} c_i g_i l_i M(\beta)^{-1/2} - \frac{1}{2} c_c g_c L_{\mathrm{mt}} M\beta^{-3/2}$$

For minimum cost, $\frac{d}{d\beta} C_t = 0$

$$\frac{1}{2} c_i g_i l_i M(\beta)^{-1/2} = \frac{1}{2} c_c g_c L_{\mathrm{mt}} M\beta^{-3/2}$$

$$c_i g_i l_i = c_c g_c L_{\mathrm{mt}} \frac{A_c}{A_i}$$

Optimum Design

Design for Minimum Cost

$$c_i g_i l_i A_i = c_c g_c L_{\mathbf{mt}} A_c$$

$$c_i G_i = c_c G_c$$

$$C_i = C_c$$

Hence for minimum cost, the cost of iron must be equal to the cost of copper.

Similarly,

For minimum volume of transformer,

$$G_i g_i = G_c g_c \ or \ \ G_i G_c = g_i g_c$$

Volume of iron = Volume of Copper

For minimum weight of transformer,

Weight of iron = Weight of Conductor

$$G_i = G_c$$

For minimum loss,

Iron loss = I^2R loss in conductor

$$P_i = x^2 P_c$$

Optimum Design

Design for Minimum Loss and Maximum Efficiency

Variable losses = Constant losses

$$P_i P_c = \frac{p_i G_i}{p_c G_c}$$

$$x^2 = \frac{p_i G_i}{p_c G_c} \quad or \quad \frac{G_i}{G_c} = x^2 \frac{p_c}{p_i}$$

for maximum efficiency

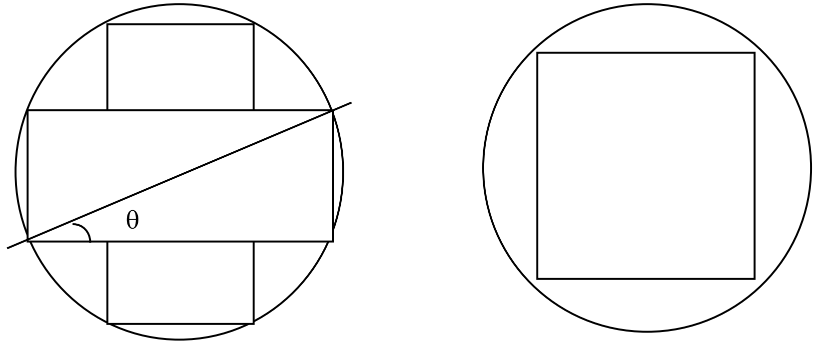
Design of Core

- Core type transformer : Rectangular/Square /Stepped cross section
- Shell type transformer : Rectangular cross section

Design of Core

Square & Stepped Core

- Used when circular coils are required for high voltage distribution and power transformer.
- Circular coils are preferred for their better mechanical strength.



- Circle representing the inner surface of the tubular form carrying the windings (Circumscribing Circle)

Design of Core

Square & Stepped Core

- Diameter of Circumscribing circle is larger in Square core than Stepped core with the same area of cross section.
- Thus the length of mean turn(L_{mt}) is reduced in stepped core and reduces the cost of copper and copper loss.
- However, with large number of steps, a large number of different sizes of laminations are used.

Design of Core

Square Core

- Gross core area includes insulation area
- Net core area excludes insulation area

Area of Circumscribing circle i $\frac{\pi}{4}d^2$

Ratio of net core area to Area of Circumscribing circle is

$$\frac{0.45d^2}{\frac{\pi}{4}d^2} = 0.58$$

Ratio of gross core area to Area of Circumscribing circle is

$$\frac{0.5d^2}{\frac{\pi}{4}d^2} = 0.64$$

Design of Core

Square Core

Let, d - diameter of circumscribing circle

a – side of square

Diameter, $d = \sqrt{a^2 + a^2} = \sqrt{2a^2} = \sqrt{2} \cdot a$

$$a = \frac{d}{\sqrt{2}}$$

Gross core area, $A_{gi} = Area\ of\ square = a^2 = \left(\frac{d}{\sqrt{2}}\right)^2$

$$A_{gi} = 0.5d^2$$

Let the stacking factor, S_f=0.9

Net core area, $A_i = 0.9 \times 0.5\, d^2 = 0.45\, d^2$

Design of Core

Square Core

Useful ratio in design – Core area factor,

$$K_C = \frac{\text{Net Core area}}{\text{Square of Circumscribing Circle}}$$

$$= \frac{A_i}{d^2} = \frac{0.45\,d^2}{d^2} = 0.45$$

Design of Core

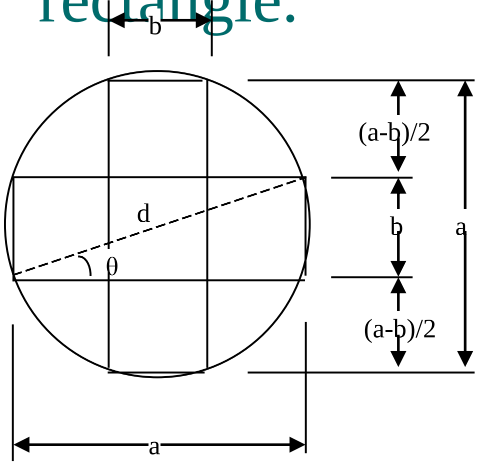
Stepped Core or Cruciform Core

Let,a – Length of the rectangle

b – breadth of the rectangle

d – diameter of the circumscribing circle and diagonal of the rectangle.

θ – Angle b/w the diagonal and length of the rectangle.



- The max. core area for a given ‘d’ is obtained by the max value of ‘θ’
- For max value of ‘θ’,

$$\frac{dA_{gi}}{d\theta} = 0$$

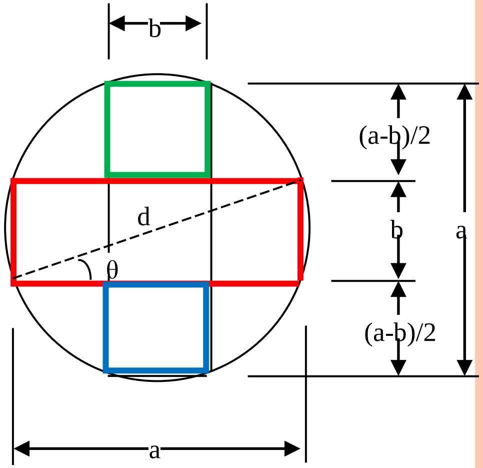
- From the figure,

$$\cos\theta = \frac{a}{d} \Rightarrow \therefore a = d\cos\theta$$

$$\sin\theta = \frac{b}{d} \Rightarrow \therefore b = d\sin\theta$$

Design of Core

Stepped Core or Cruciform Core



Two stepped core can be divided in to 3 rectangles.

Referring to the fig shown,

$$\text{Gross core area}, A_{gi} = ab + \left(\frac{a-b}{2}\right)b + \left(\frac{a-b}{2}\right)b$$

$$= ab + \frac{2(a-b)}{2}b$$

$$= ab + ab - b^2 = 2ab - b^2$$

On substituting ‘a’ and ‘b’ in the above equations,

$$A_{gi} = 2(d\cos\theta)(d\sin\theta) - (d\sin\theta)^2$$

$$A_{gi} = 2d^2\cos\theta\sin\theta - d^2\sin^2\theta$$

$$A_{gi} = d^2\sin 2\theta - d^2\sin^2\theta$$

For max value of ‘θ’,

$$\frac{dA_{gi}}{d\theta} = 0$$

Design of Core

Stepped Core or Cruciform Core

i.e., $$\frac{dA_{gi}}{d\theta} = d^2 2\cos 2\theta - d^2(2\sin\theta\cos\theta) = 0$$

$$d^2 2\cos 2\theta = d^2(2\sin\theta\cos\theta)$$

$$2\cos 2\theta = \sin 2\theta$$

$$\frac{\sin 2\theta}{\cos 2\theta} = 2$$

$$\tan 2\theta = 2$$

$$2\theta = \tan^{-1}(2)$$

$$\theta = \frac{1}{2}\tan^{-1}(2) = 31.72^0$$

Therefore, if the $\theta=31.72^0$, the dimensions ‘a’ & ‘b’ will give maximum area of core for a specified ‘d’.

$$\cos\theta = \frac{a}{d} \Rightarrow \therefore a = d\cos\theta \Rightarrow a = d\cos(31.72^0) = 0.85\,d$$

$$\sin\theta = \frac{b}{d} \Rightarrow \therefore b = d\sin\theta \Rightarrow b = d\sin(31.72^0) = 0.53\,d$$

Design of Core

Stepped Core or Cruciform Core

Gross core area,

$$A_{gi} = 2ab - b^2$$

$$A_{gi} = 2(0.85d)(0.53d) - (0.53d)^2$$

$$A_{gi} = 0.618d^2$$

Let stacking factor, $S_f = 0.9$,

Net core area, A_i = Stacking factor X Gross Core area

$$A_i = 0.9 \times 0.618d^2 = 0.56d^2$$

The ratios,

$$\frac{\text{Net core area}}{\text{Area of Circumscribing circle}} = \frac{0.56d^2}{\frac{\pi}{4}d^2} = 0.71$$

$$\frac{\text{Gross core area}}{\text{Area of Circumscribing circle}} = \frac{0.618d^2}{\frac{\pi}{4}d^2} = 0.79$$

Design of Core

Stepped Core or Cruciform Core

Core area factor,

$$K_C = \frac{\text{Net Core area}}{\text{Square of Circumscribing Circle}}$$

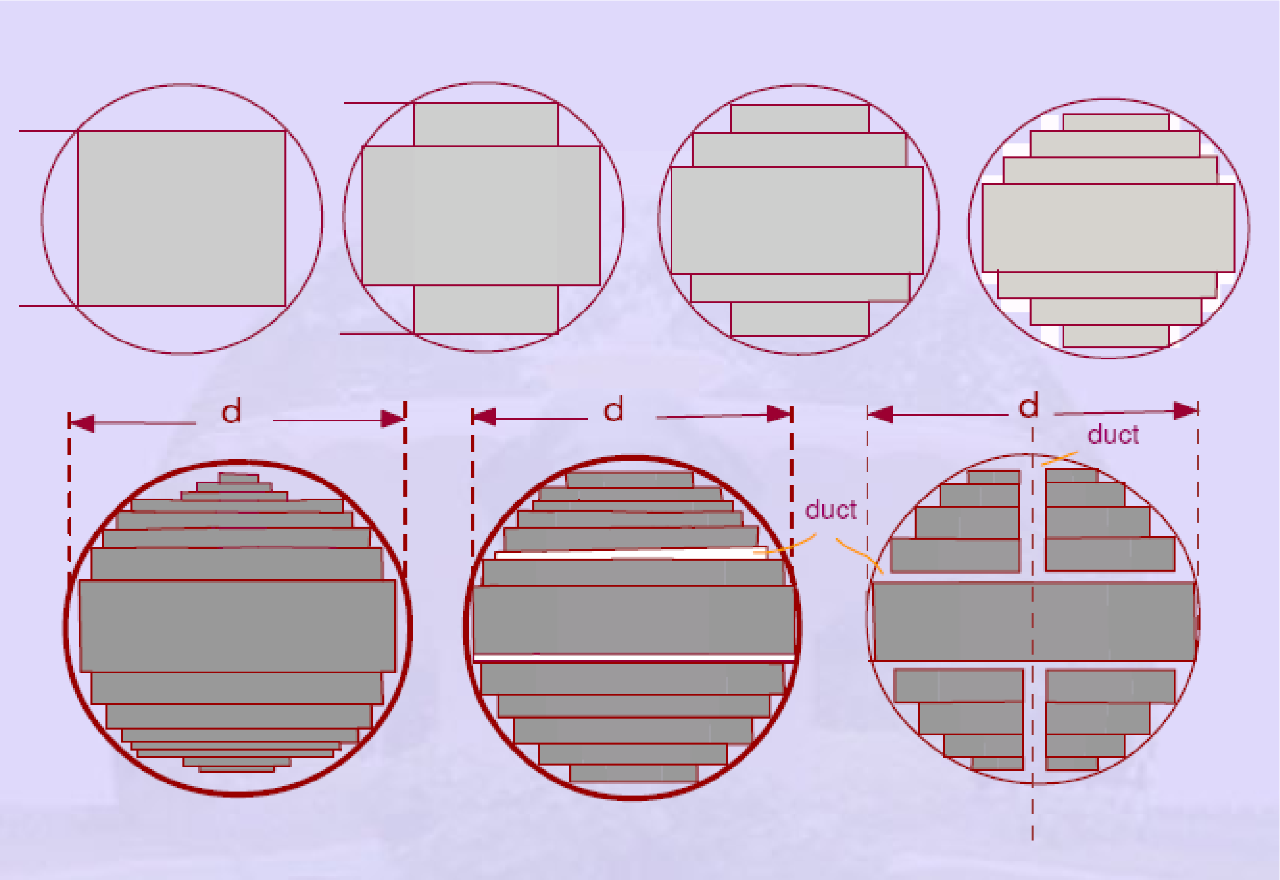
$$= \frac{A_i}{d^2} = \frac{0.56\,d^2}{d^2} = 0.56$$

Ratios of Multi-stepped Cores,

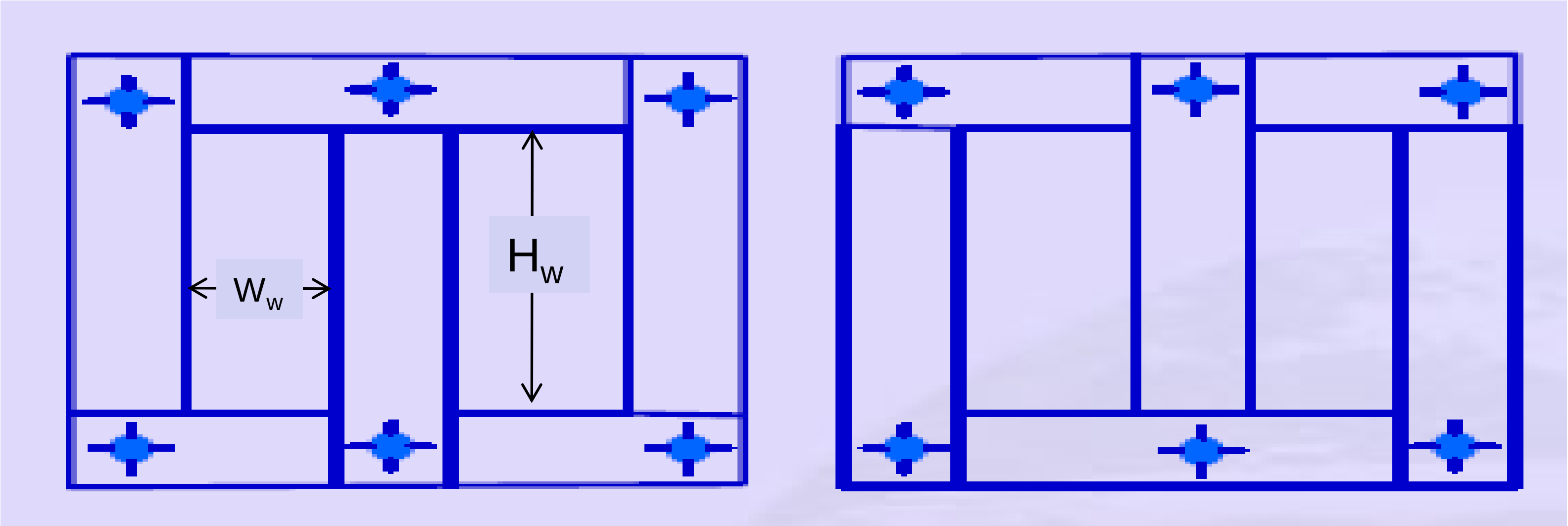
Ratio	Square Core	Cruciform Core	3-Stepped Core	4-Stepped Core
$\frac{\text{Gross core area}}{\text{Area of Circumscribing circle}}$	0.64	0.79	0.84	0.87
$\frac{\text{Net core area}}{\text{Area of Circumscribing circle}}$	0.58	0.71	0.75	0.78
Core area factor, K_C	0.45	0.56	0.6	0.62

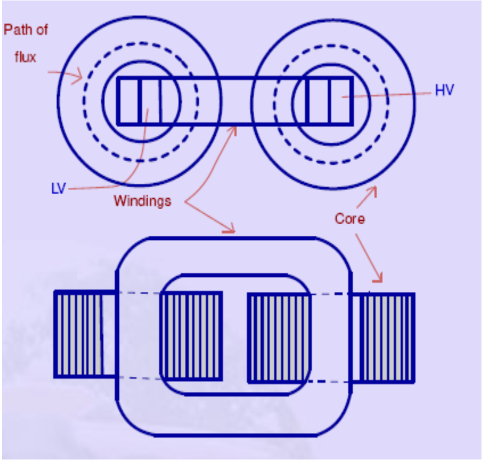
Transformer Core

Stepped Core Construction



Transformer Core



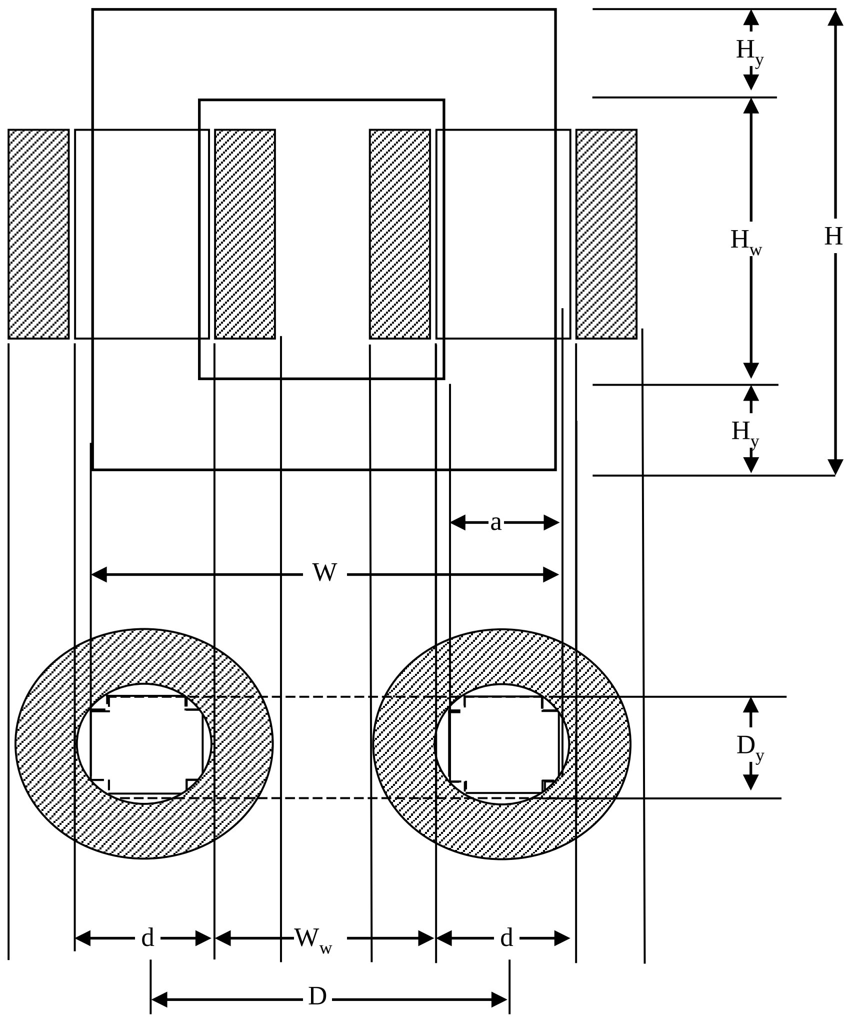


Core Type

Shell Type

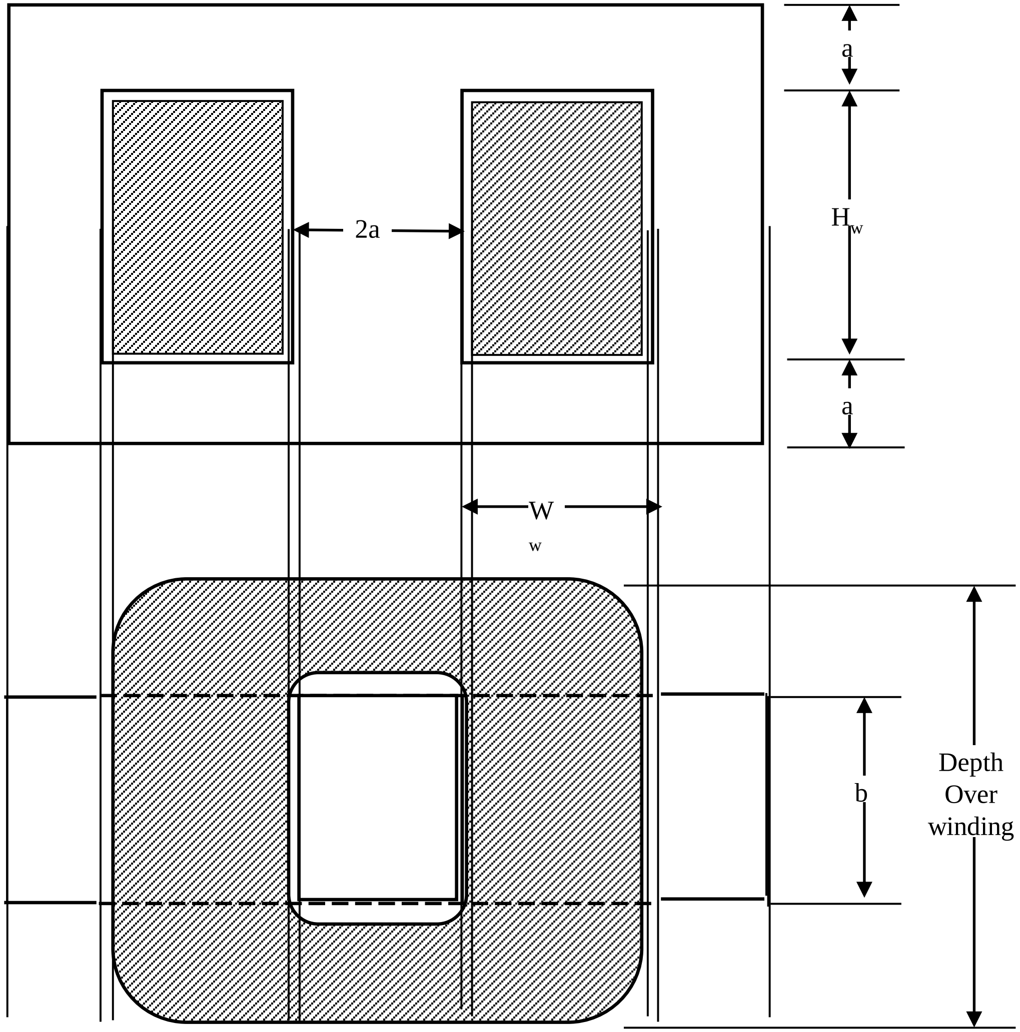
Overall Dimensions

Single phase Core Type



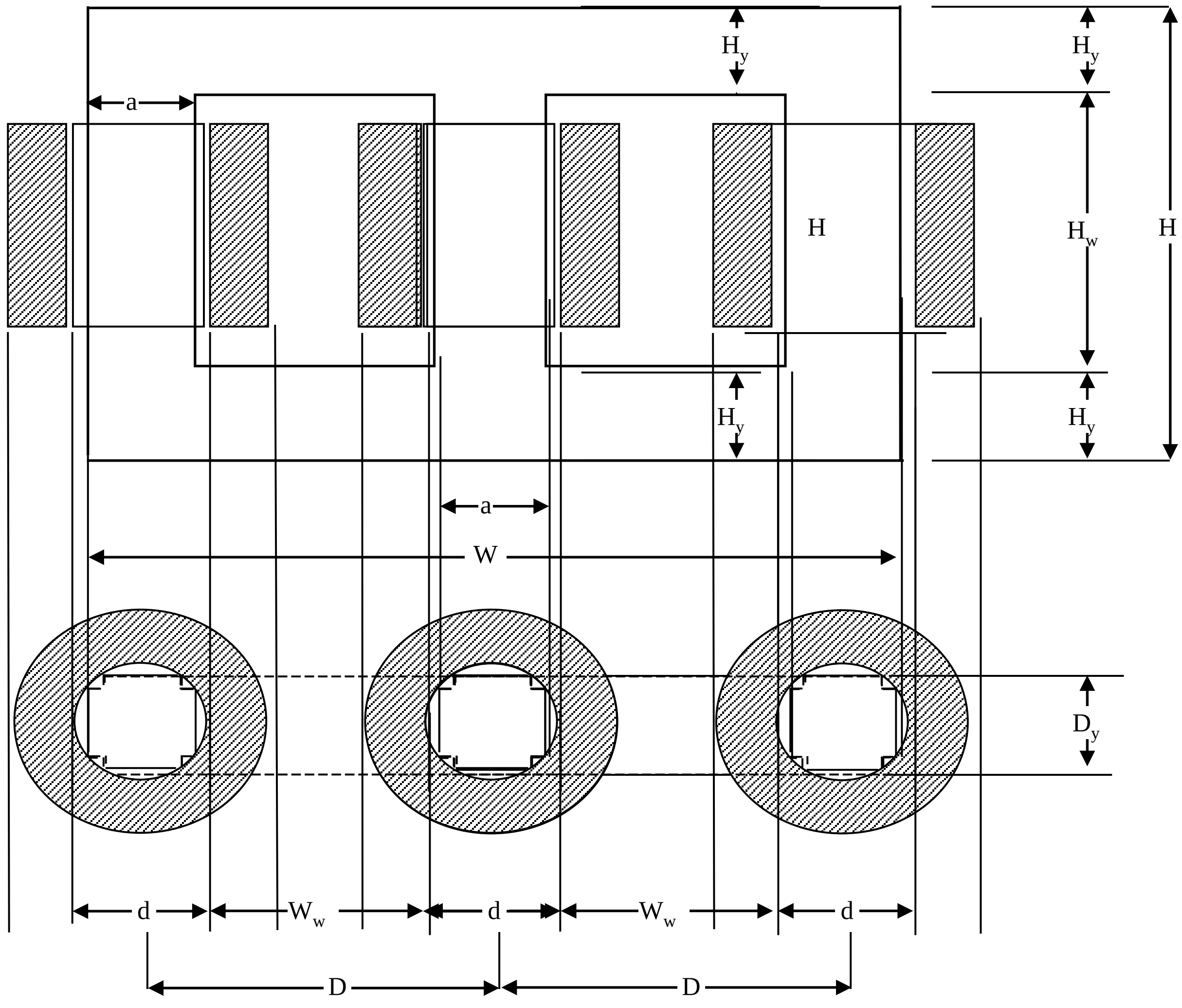
Overall Dimensions

Single phase Shell Type



Overall Dimensions

Thee phase Core Type



Design of Winding

- Transformer windings: HV winding & LV winding
- Winding Design involves:
  - Determination of no. of turns: based on kVA rating & EMF per turn
  - Area of cross section of conductor used: Based on rated current and Current density
- No. of turns of LV winding is estimated first using given data.
- Then, no. of turns of HV winding is calculated to the voltage rating.

No. of turns in LV winding, $T_{LV} = \dfrac{V_{LV}}{E_t}\ (or)\ \dfrac{AT}{I_{LV}}$

where, V_{LV} = Rated voltage of LV winding

I_{LV} = Rated Current of LV winding

Design of Winding

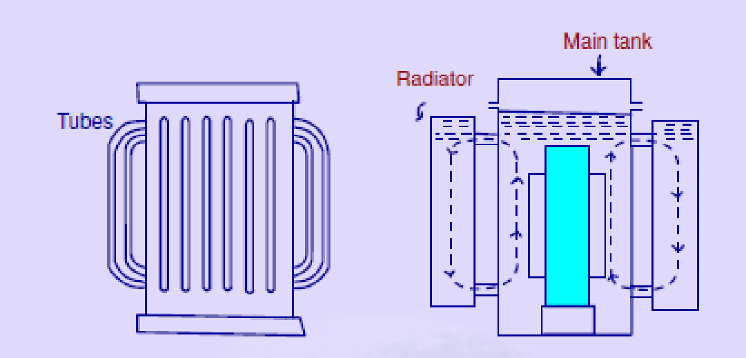
$$\text{No. of turns in HV winding, } T_{HV} = T_{LV} \times \frac{V_{HV}}{V_{LV}}$$

$where, V_{HV}$ – Rated voltage of HV winding

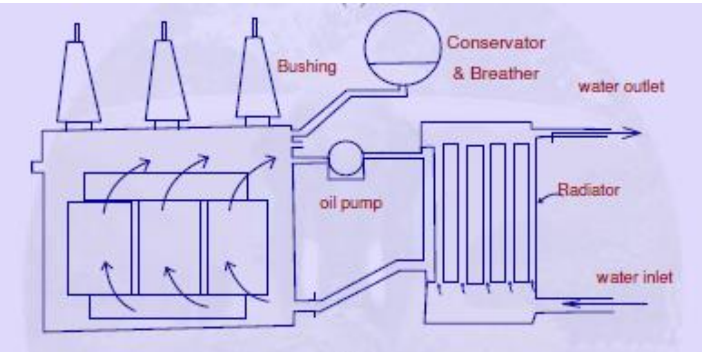
Transformer Winding

- Types of transformer windings are,
  - Concentric
  - Sandwich
    - Disc
    - Cross over
    - Helical

Constructional Details



(a)



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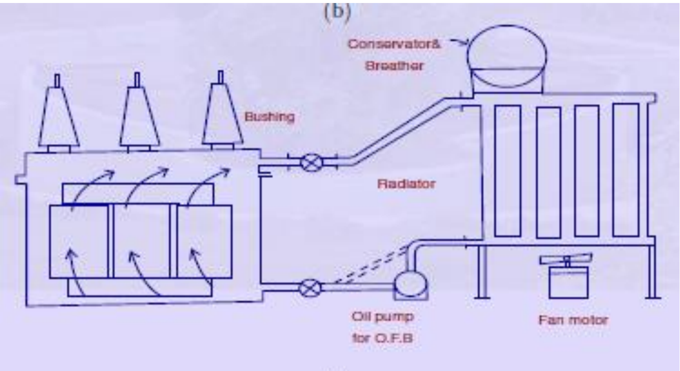
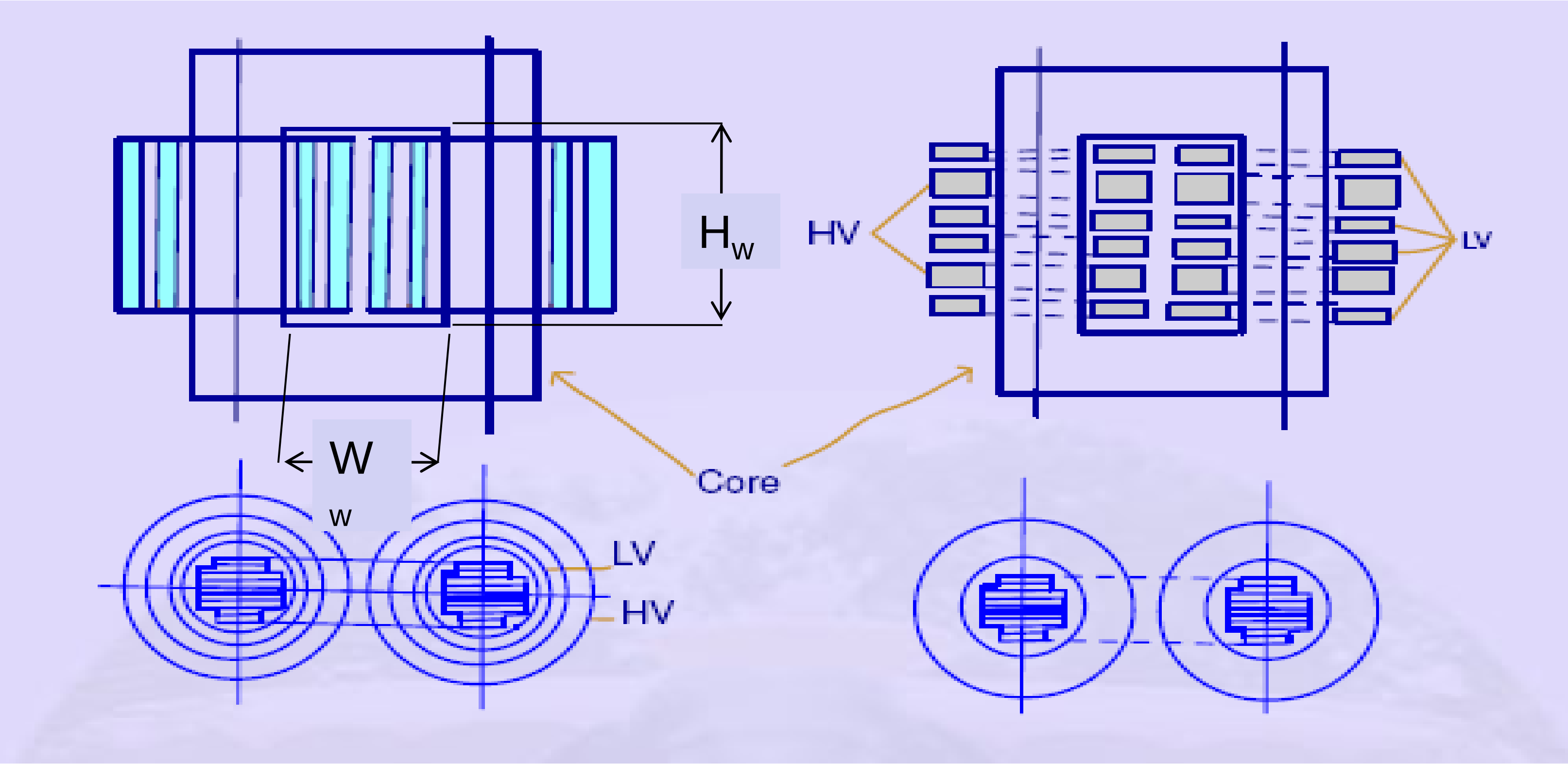
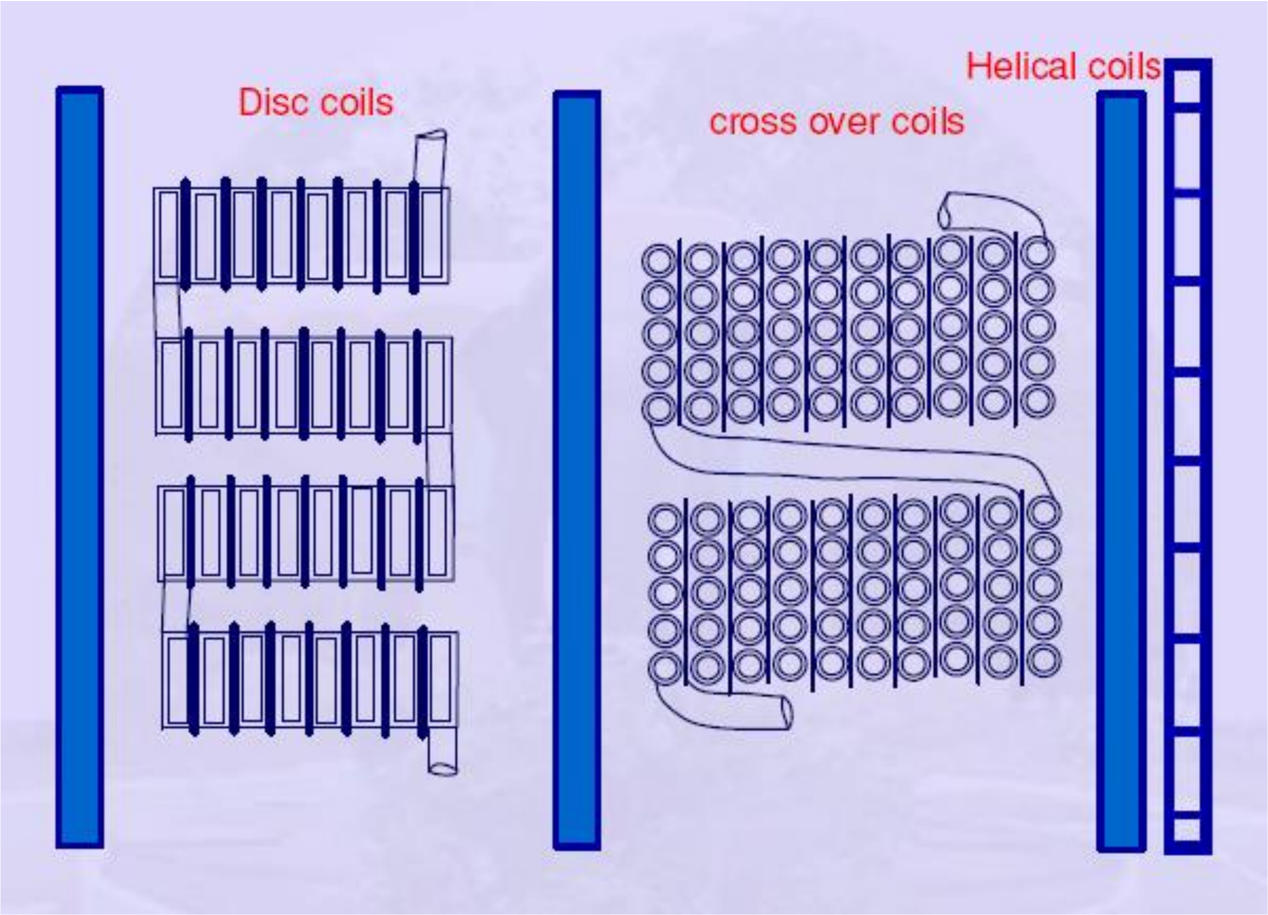


(c)

Transformer Winding



Transformer Winding



Insulations

- Dry type Transformers:
  - Varnish
  - Enamel
- Large size Transformers:
  - Unimpregnated paper
  - Cloths
    - Immersed in Transformer oil – insulation & coolent

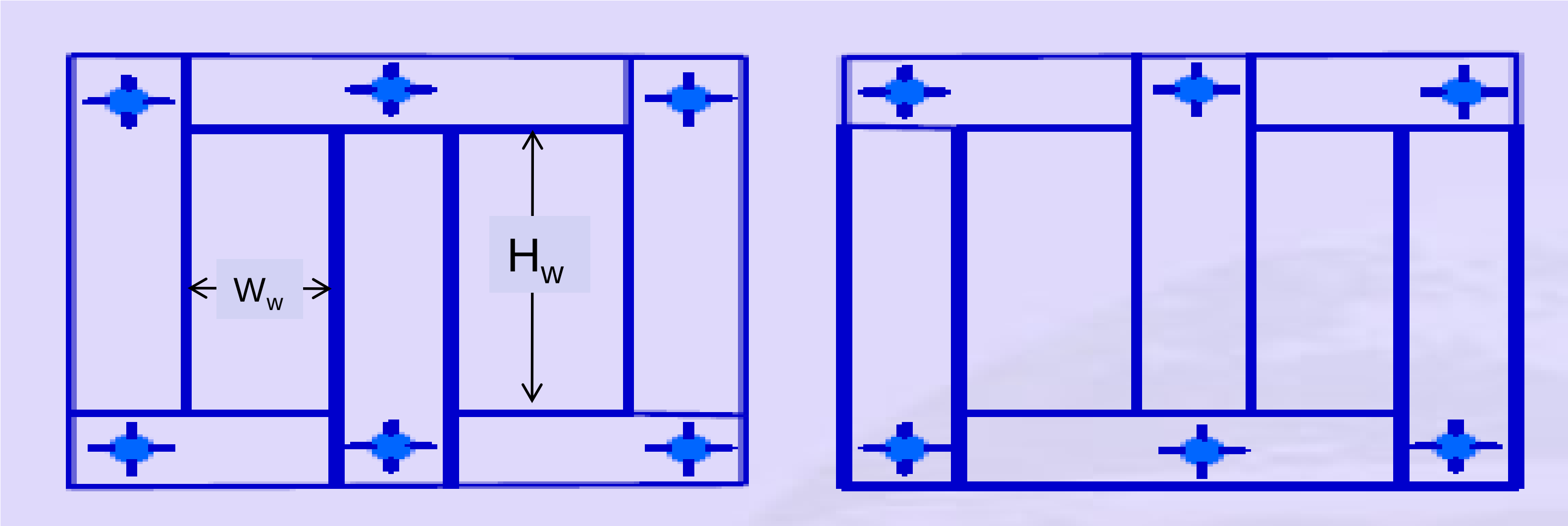
Comparison between Core & Shell Type

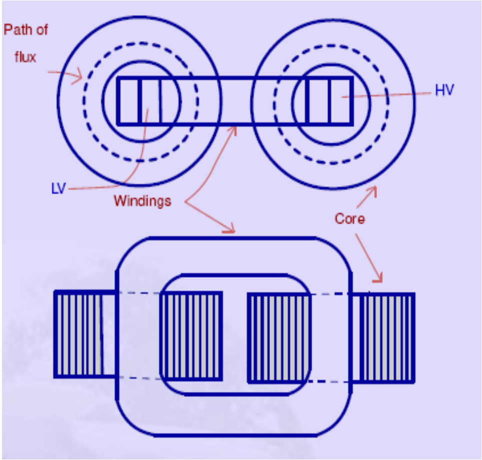
Description	Core Type	Shell Type
Construction	Easy to assemble & Dismantle	Complex
Mechanical Strength	Low	High
Leakage reactance	Higher	Smaller
Cooling	Better cooling of Winding	Better cooling of Core
Repair	Easy	Hard
Applications	High Voltage & Low output	Low Voltages & Large Output

Classification on Service

Details	Distribution transformer	Power Transformer
Capacity	Upto 500kVA	Above 500kVA
Voltage rating	11,22,33kV/440V	400/33kV;220/11kV…
Connection	Δ/Y, 3φ, 4 Wire	Δ/Δ; Δ/Y, 3φ, 4 Wire
Flux Density	Upto 1.5 wb/m^2	Upto 1.7 wb/m^2
Current Density	Upto 2.6 A/mm^2	Upto 3.3 A/mm^2
Load	100% for few Hrs, Part loadfor some time, No-load for few Hrs	Nearly on Full load
Ratio of Iron Loss to Cu loss	1:3	1:1
Regulation	4 to 9%	6 to 10%
Cooling	Self oil cooled	Forced Oil Cooled

Transformer Core





Core Type

Shell Type

Cooling of transformers

Temperature rise in plain walled tanks

- Transformer wall dissipates heat in radiation & convection.
- For a temperature rise of 40^0C above the ambient temperature of 20^0C, the heat dissipations are as follows:
  - Specific heat dissipation by radiation, $\lambda_{rad}=6\ W/m^2.^0C$
  - Specific heat dissipation by convection, $\lambda_{conv}=6.5\ W/m^2.^0C$
  - Total heat dissipation in plain wall $12.5\ W/m^2.^0C$

S_t – Heat dissipating surface

- Heat dissipating surface of tank : Total area of vertical sides+ One half area of top cover(Air cooled) (Full area of top cover for oil cooled)

Cooling of transformers

Transformer Oil as Cooling Medium

- Specific heat dissipation due to convection is,

$$\lambda_{conv} = 40.3 \left(\frac{\theta}{H}\right)^{14} W/m^2.^0C$$

where, θ - Temperature difference of the surface relative to oil, ^0C

H – Height of dissipating surface, m

- The average working temperature of oil is 50-60^{0}C.
- For $\theta = 20^0 C \wedge H = 0.5 \ to \ 1 m,$

$$\lambda_{conv} = 80 \text{ to } 100 \text{ W/m}^2.^0C.$$

The value of the dissipation in air is 8 W/m^2.^{0}C. i.e, 10 times less than oil.

Design of tanks with cooling tubes

- Cooling tubes increases the heat dissipation
- Cooling tubes mounted on vertical sides of the transformer would not proportional to increase in area. Because, the tubes prevents the radiation from the tank in screened surfaces.
- But the cooling tubes increase circulation of oil and hence improve the convection
- Circulation is due to effective pressure heads
- Dissipation by convection is equal to that of 35% of tube surface area. i. e., 35% tube area is added to actual tube area.

Design of tanks with cooling tubes

Let, Dissipating surface of tank – S_t

Dissipating surface of tubes – XS_t

Loss dissipated by surface of the tank by radiation and convection =

$$(6+6.5)S_t = 12.5\,S_t$$

Loss dissipated by tubes by convection

Total loss dissipated by walls and tubes

$$6.5 \times \frac{135}{100} \times XS_t = 8.8XS_t \qquad 12.5S_t + 8.8XS_t = (12.5+8.8X)S_t \rightarrow (1)$$

Actual total area of tank walls and tubes = $S_t + XS_t = S_t(1+X)$

Design of tanks with cooling tubes

$$\text{Loss dissipated per } m^2 \text{ of dissipating surface} = \frac{\text{Total losses dissipated}}{\text{Total area}}$$

$$\text{Loss dissipated per } m^2 \text{ of dissipating surface} = \frac{S_t(12.5+8.8X)}{S_t(1+X)} = \frac{(12.5+8.8X)}{(1+X)} \rightarrow (2)$$

Temperature rise in

Transformer with cooling tubes

()

$$\theta = \frac{\text{Total loss}}{\text{Loss Dissipated}}$$

Total losses, $P_{loss} = P_i + P_c \rightarrow (3)$ From (1) and (3), we have, $\theta = \frac{P_i + P_c}{S_t(12.5+8.8X)}(12.5+8.8X) = \frac{P_i+P_c}{\theta S_t} 8.8X = \frac{P_i+P_c}{\theta S_t} - 12.5 \Rightarrow$

$$X = \frac{1}{8.8}\left(\frac{P_i + P_c}{\theta S_t} - 12.5\right)$$

Design of tanks with cooling tubes

$$\text{Total area of cooling tubes} = \frac{1}{8.8}\left(\frac{P_i + P_c}{\theta\, S_t} - 12.5\right)S_t = \frac{1}{8.8}\left(\frac{P_i + P_c}{\theta} - 12.5 S_t\right) \rightarrow (5)$$

Let, l_t – *Length of tubes*

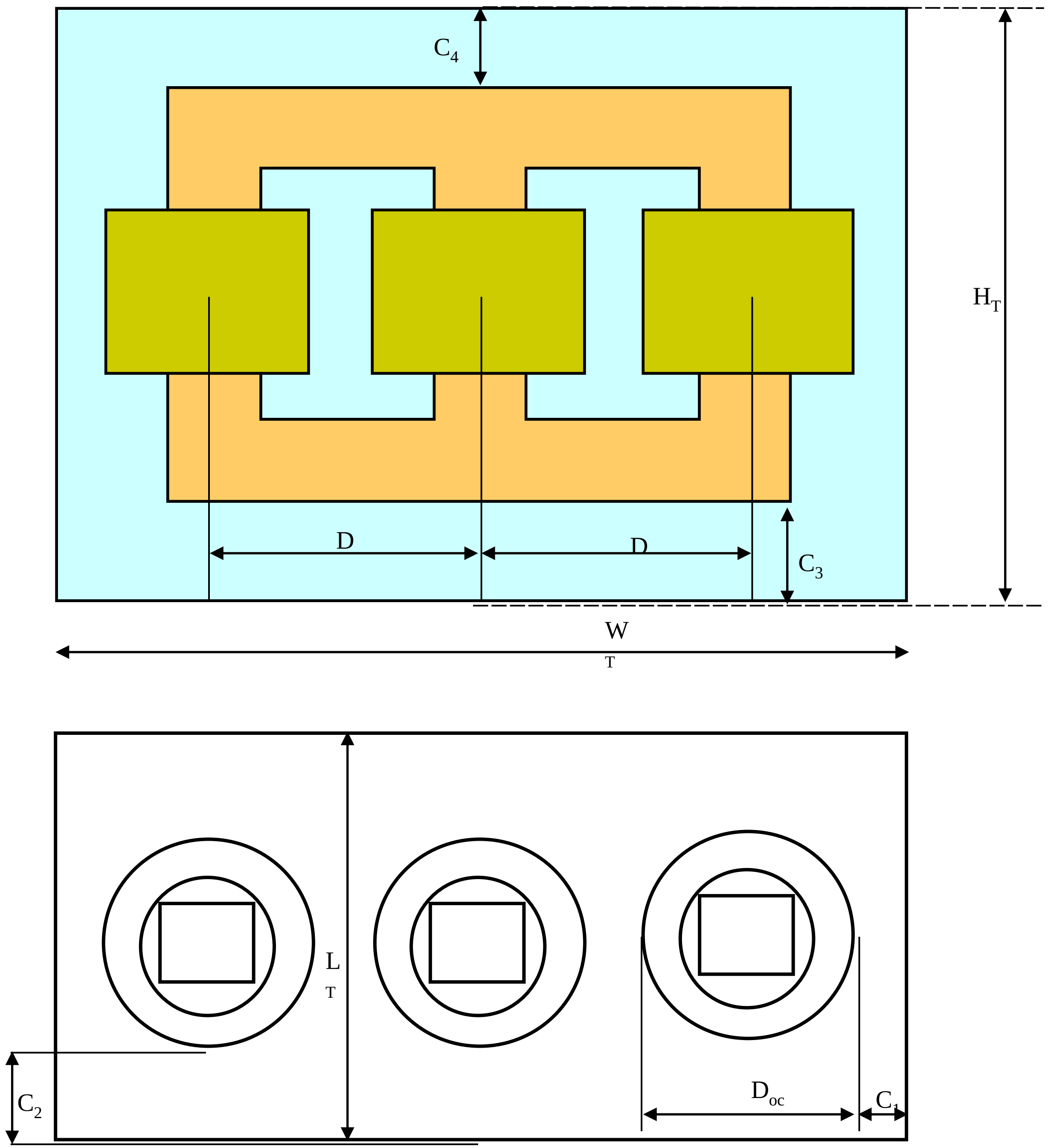
d_t – *Diameter of tubes*

$\therefore$ *Surface area of tubes* $= \pi\, d_t l_t$

$$\text{Total number of tubes}, n_t = \frac{\text{Total area of tubes}}{\text{Area of each tube}}$$

$$n_t = \frac{1}{8.8\pi\, d_t l_t}\left(\frac{P_i + P_c}{\theta} - 12.5 S_t\right) \rightarrow (6)$$

- Standard diameter of cooling tube is 50mm & length depends on the height of the tank.
- Center to center spacing is 75mm.



C_4
H_T
D
D
C_3
W_T
L_T
C_2
D_{oc}
C_1

Design of tanks with cooling tubes

- Dimensions of the tank:

  Let, C_1 – Clearance b/w winding and tank along width

  C_2 - Clearance b/w winding and tank along length

  C_3 – Clearance b/w the transformer frame and tank at the bottom

  C_4 - Clearance b/w the transformer frame and tank at the top

  D_{oc} – Outer diameter of the coil.

  Width of the tank, $W_T = 2D + D_{oc} + 2\,C_1$ (For 3ϕ Transformer)

  $= D + D_{oc} + 2\,C_1$ (For 1ϕ Transformer)

  Length of the tank, $L_T = D_{oc} + 2\,C_2$

  Height of the tank, $H_T = H + C_3 + C_4$

Design of tanks with cooling tubes

- Clearance on the sides depends on the voltage & power ratings.
- Clearance at the top depends on the oil height above the assembled transformer & space for mounting the terminals and tap changer.
- Clearance at the bottom depends on the space required for mounting the frame.

Voltage kV	KVA Rating	Clearance mm		
		b or c1	l or c2	h
11 kV or less	Less than 1000	40	50	450
About 11 kV	1000 to 5000	70	90	420
and upto 33 kV	Less than 1000	75	100	550
	1000 to 5000	85	125	550

- A 250 kVA , 6600/400 V , 3 PHASE CORE TYPE TRANSFORMER HAS A TOTAL LOSS OF 4800 W at full load. The transformer tanks is 1.25 m in height and 1m * 0.5 m in plan. Design a suitable scheme for tubes if the average temperature rise is to be limited to 35 degree c. The diameter of tube is 50 mm and are spaced 75 mm from each other . The average heights of tubes is 1.05 m. specific heat dissipation due to radiation and convection is respectively 6 and 6.5 W/m2- deg. C
- Assume that convection is improved by 35 per cent due to provision of tubes.

Solution. Area of plane tank $S_t = 2(1 + 0.5) \times 1.25 = 3.75\ m^2$

Let the tube area be xSt.

$\therefore$ Total dissipating surface $= (1 + x)\,S_t = 3.75\,(1 + x)$

$$\text{Specific loss dissipation} = \frac{4800}{3.75(1+x)\times 35} = \frac{36.5}{1+x}\ \text{W/m}^2-{}^\circ\text{C}$$

$$\text{From Eqn. 5.98 loss dissipated} = \frac{12.5+8.8x}{1+x}\ \text{W/m}^2-{}^\circ\text{C}$$

$$\frac{12.5+8.8x}{1+x} = \frac{36.5}{1\times x} \quad \text{or} \quad x = 2.73$$

$\therefore$ Area of tubes $= 2.73 \times 3.75 = 10.23\ m^2$.

Wall area of each tube $= \pi d_t\, l_t = \pi \times 0.05 \times 1.05 = 0.165\ m^2$.

$\therefore$ Total number of tubes to be provided $= 10.23/0.165 = 62$.

$\therefore$ Total tubes provided $= 2 \times 12 + 2 \times 11 + 2 \times 5 + 2 \times 4 = 64.$

Fig. 5.87 shows the arrangement for tubes.

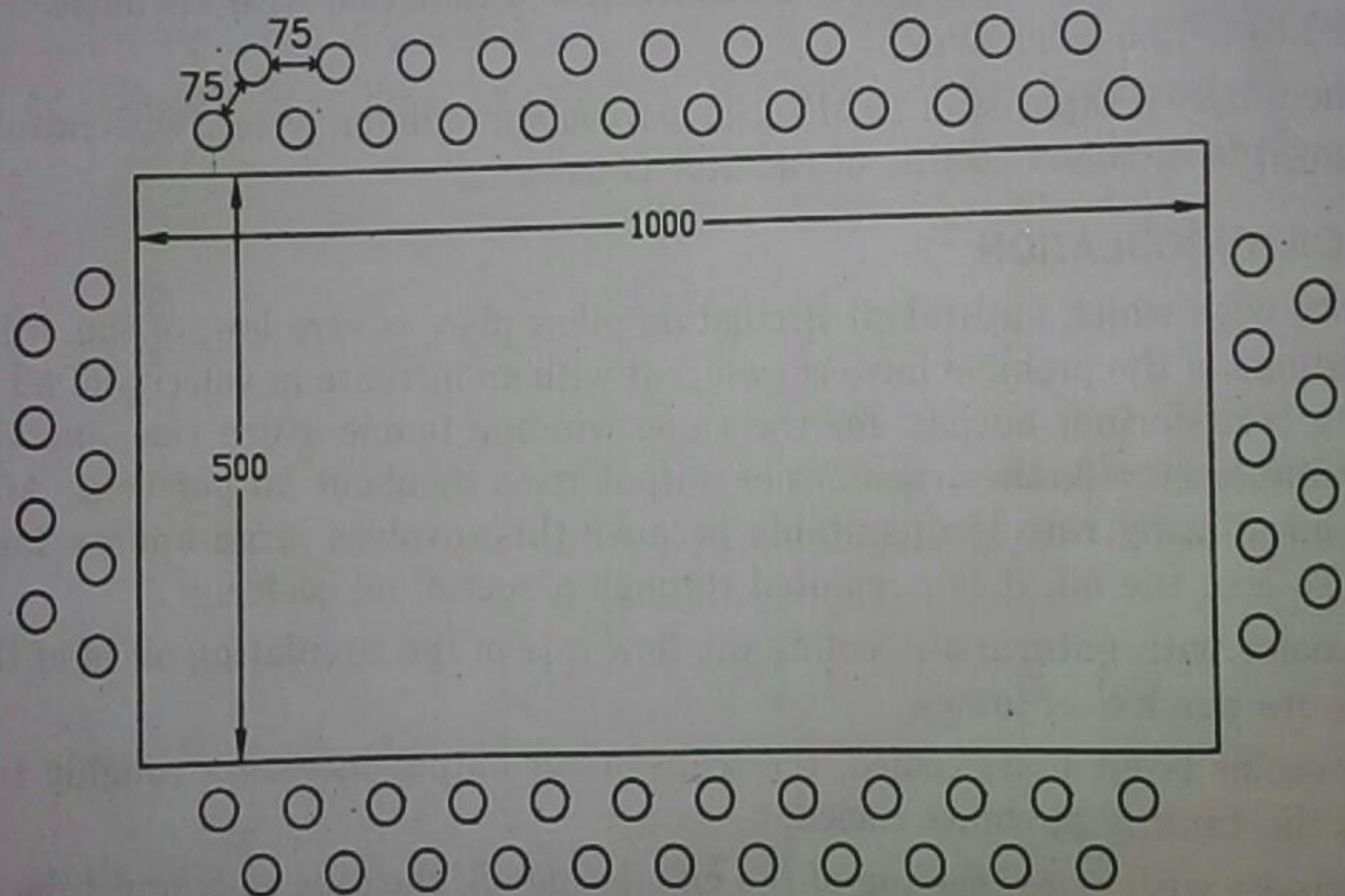


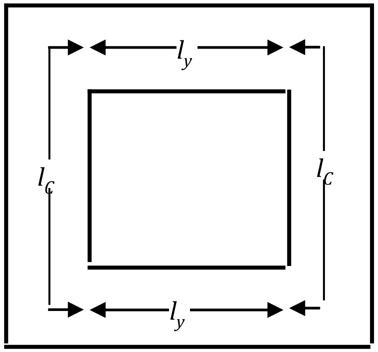
Fig. 5.87. Arrangement of cooling tubes.

Estimation of No-load Current

- No-load Current of Transformer:
  - Magnetizing Component
    - Depends on MMF required to establish required flux
  - Loss Component
    - Depends on iron loss

Estimation of No-load Current

No-load current of Single phase Transformer



Total Length of the core = $2l_c$

Total Length of the yoke = $2l_y$

Here, l_c=H_w=Height of Window

l_y= W_w=Width of Window

MMF for core=MMF per metre for max. flux density in core X Total length of Core = $at_c \times 2l_c = 2\, at_c\, l_c$

MMF for yoke=MMF per meter for max. flux density in yoke X Total length of yoke = $at_y \times 2l_y = 2\, at_y\, l_y$

Total Magnetizing MMF,AT_0=MMF for Core+MMF for Yoke+MMF for joints = $2\, at_c\, l_c + 2\, at_y\, l_y$ +MMF for joints

The values of at_c & at_y are taken from B-H curve of transformer steel.

Estimation of No-load Current

No-load current of Single phase Transformer

Max. value of magnetizing current $= AT_0/T_p$

If the magnetizing current is sinusoidal then,

RMS value of magnetizing current, $I_m = AT_0/\sqrt{2}T_p$

If the magnetizing current is not sinusoidal,

RMS value of magnetizing current, $I_m = AT_0/K_{pk}T_p$

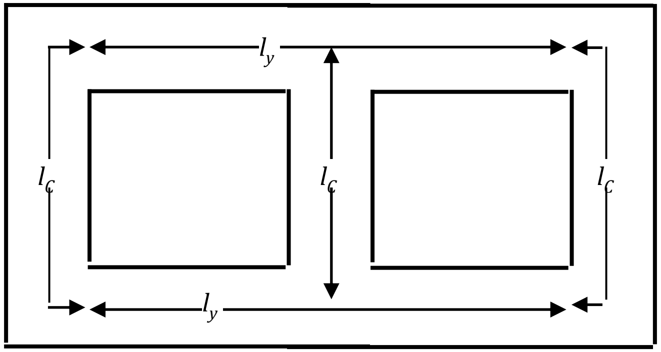
The loss component of no-load current, $I_l = P_i/V_p$

Where, P_i – Iron loss in Watts V_p – Primary terminal voltage

Iron losses are calculated by finding the weight of cores and yokes. Loss per kg is given by the manufacturer. No-load current,

$$I_0 = \sqrt{I_m^2 + I_l^2}$$

Estimation of No-load Current



Total Magnetizing MMF,AT_0=MMF for Core+MMF for Yoke+MMF for joints

= 3 $at_c\, l_c$ +2 $at_y\, l_y$ +MMF for joints

Total Magnetizing MMF,$AT_{0\ \text{per phase}}$=MMF for Core+MMF for Yoke+MMF for joints

= (3$at_c\, l_c$ +2 $at_y\, l_y$ +MMF for joints)/3