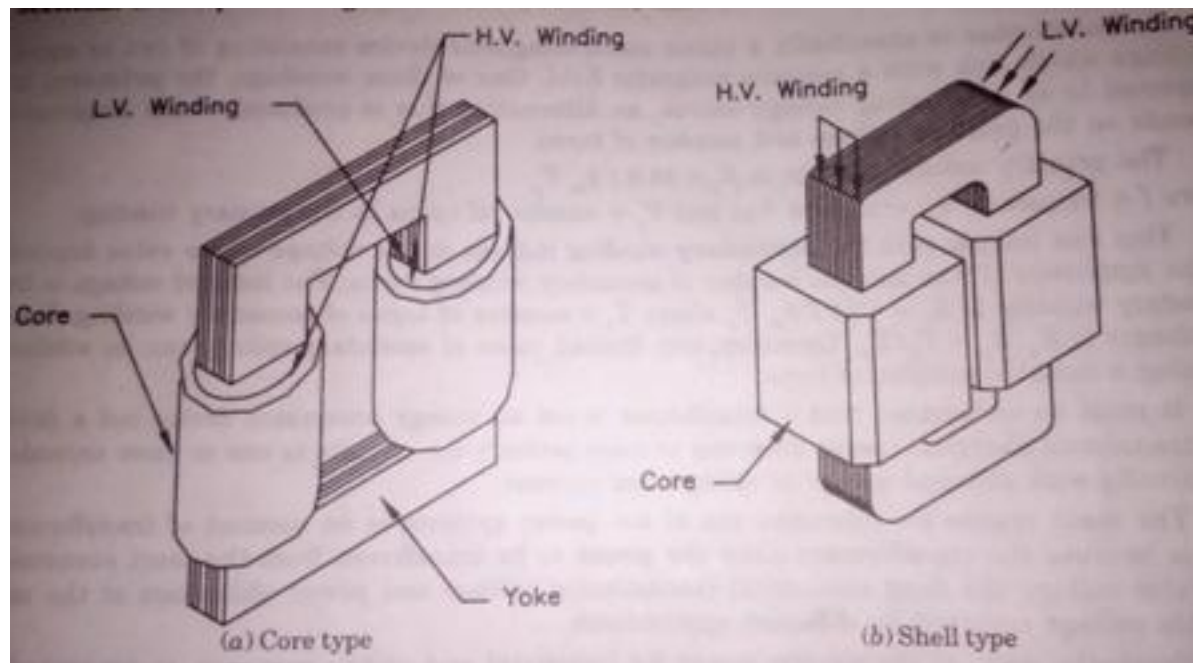


DESIGN OF TRANSFORMER

Classification of transformer

Depending upon the type of construction used:

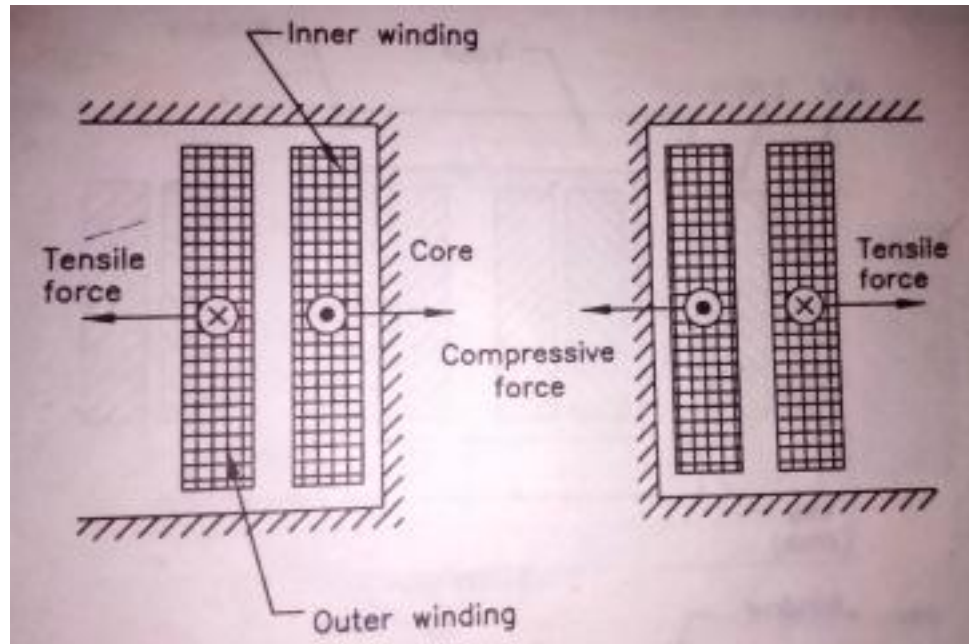
- I. Core type
- II. Shell type



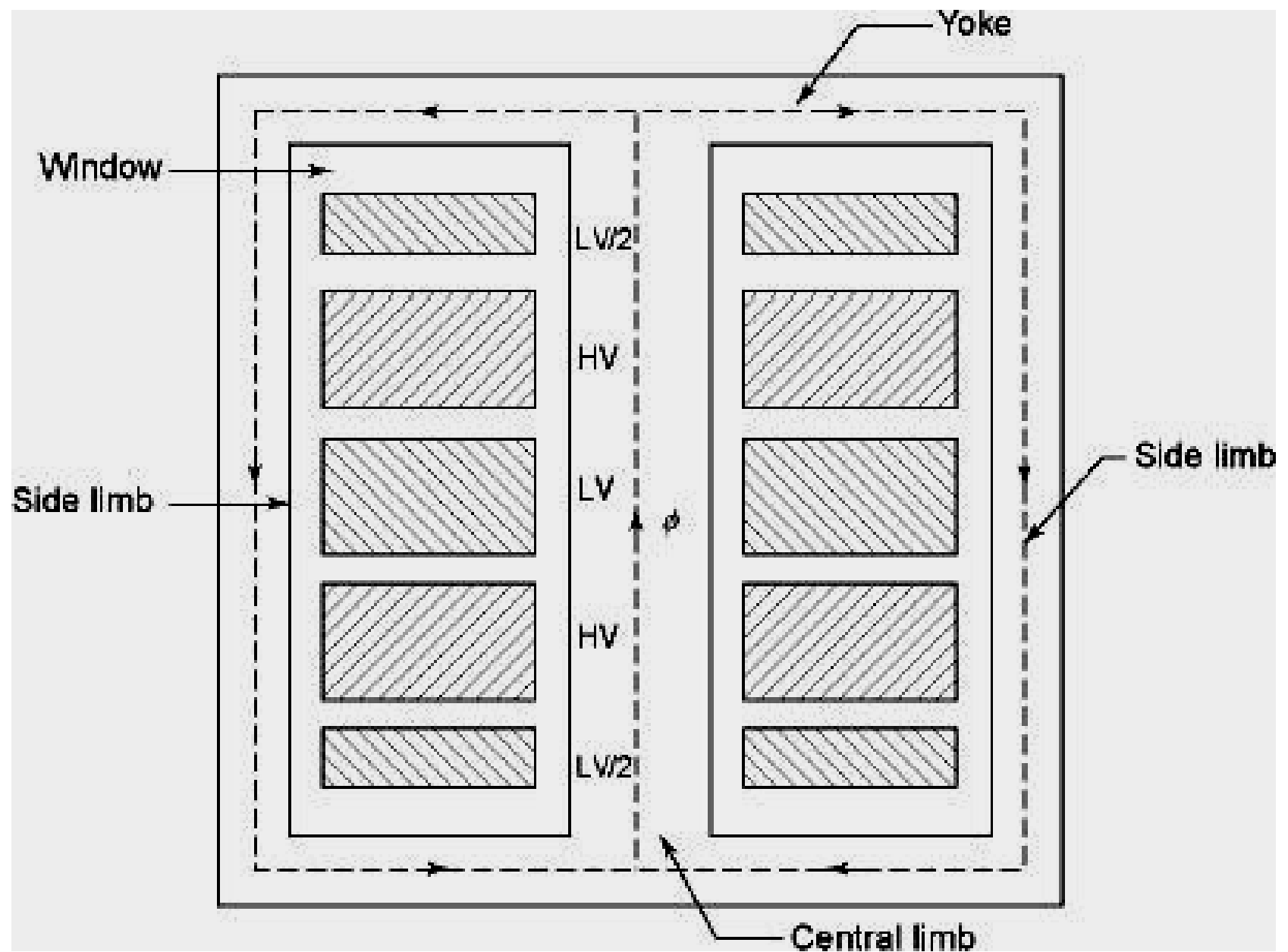
Comparison of core type and shell type transformers:-

- I. Construction:-** Core type transformers are much simpler in design and permit easier assembly and insulation of winding.
- II. Mechanical forces:-** The forces produced between windings is proportional to the product of the currents carried by them. Very large electromagnetic forces are produced when secondary winding is short circuited. Since the windings carry currents in opposite direction, there exists a force of repulsion between them. Hence, the inner winding experiences a compressive force and outer winding experiences a tensile force.

In a shell type transformer, windings have greater capability of withstanding forces produced under short circuit as these windings are surrounded and supported by the core. But in a core type transformer windings have a poorer mechanical strength.



- III. Leakage reactance:-** In core type transformer large space required between the high and low voltage winding, it is not possible to subdivide the winding, while, in shell type transformer the windings can be easily subdivided by using sandwich coil. So it is possible to reduce the leakage reactance of shell type transformers.
- IV. Repairs:-** The winding of core type transformer is completely accessible so coils can be easily inspected. And also core type transformer is easy to dismantle for repair. In shell type transformer, the coils are surrounded by core, therefore difficulty in inspection and repair of coils.
- V. Cooling:-** In core type transformer windings are exposed and therefore the cooling is better in winding than core. In case of shell type transformer core is exposed therefore cooling is better than winding.



CORE TYPE	SHELL TYPE
<ol style="list-style-type: none"> 1. Easy in design and construction. 2. Has low mechanical strength due to non- bracing of windings. 3. Reduction of leakage reactance is not easily possible. 4. The assembly can be easily dismantled for repair work. 5. Better heat dissipation from windings. 6. Has longer mean length of core and shorter mean length of coil turn. Hence best requirement 	<ol style="list-style-type: none"> 1. Comparatively complex. 2. High mechanical strength. 3. Reduction of leakage reactance is highly possible. 4. It cannot be easily dismantled for repair work. 5. Heat is not easily dissipated from windings since it is surrounded by core. 6. It is not suitable for EHV (Extra High voltage) requirement.

Classification on the basis of type of service:

- I. Distribution transformer
- II. Power transformer

Classification on the basis of power utility:

- I. Single phase transformer
- II. Three phase transformer

Construction of transformer

- I. Transformer core
- II. Winding
- III. Insulation
- IV. Tank
- V. Bushings
- VI. Conservator and breather
- VII. Tapping and tap changing
- VIII. Buchholz Relay
- IX. Explosion vent
- X. Transformer oil

- **The most important function performed by transformers are,**
 - Changing voltage and current level in an electric system.
 - Matching source and load impedances for maximum power transfer in electronic and control circuitry.
 - Electrical isolation.

Nomenclature

V_p , V_s = terminal voltages at primary and Secondary winding respectively, V

E_p , E_s = emf induced in the primary and secondary windings per phase, V

E_t = emf per turn, V

T_p , T_s = number of primary and secondary turns per phase

I_p , I_s = primary and secondary currents per phase , A

a_p , a_s = area of the primary and secondary winding conductors, m^2

Φ_m = main flux in weber = $A_i B_m$

B_m = Maximum value of the flux density = Φ_m / A_i tesla

A_i – Net iron area of the core or leg or limb (m^2) = $K_i A_{gi}$

K_i – Iron or stacking factor = 0.9 approximately

A_{gi} – Gross area of the core, m^2

A_c – area of copper in window, m^2

A_w – window area, m^2

D – distance between core centers, m

d = diameter of circumscribing circle, m

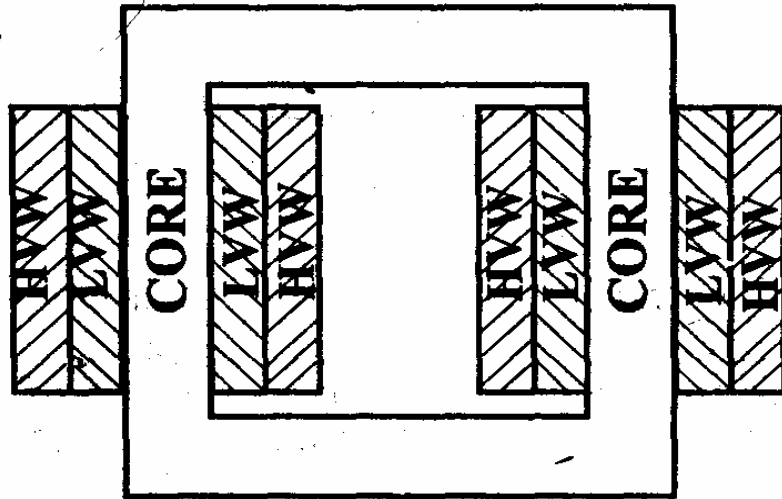
K_w – window space factor

δ - Current density (A/m^2). Assumed to be same for both LV and HV winding.

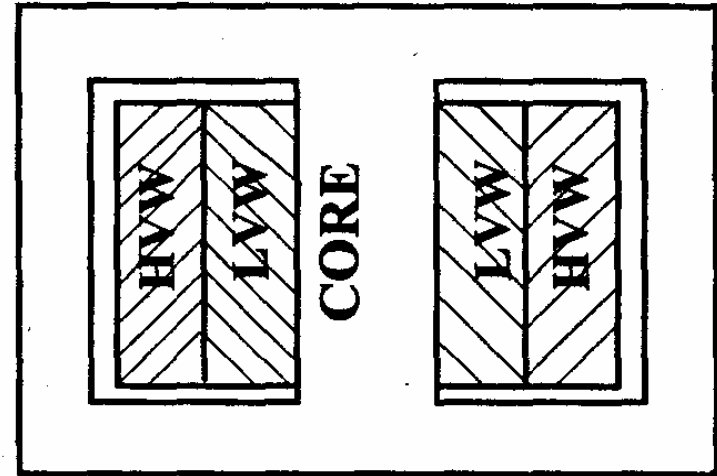
Output Equation of Transformer

- The equation which relates the rated kVA output of a transformer to the area of core and window is called output equation.
- In transformers the output kVA depends on flux density and ampere-turns.
- The flux density is related to core area and the ampere-turns is related to window area.
- The low voltage winding is placed nearer to the core in order to reduce the insulation requirement.
- The space inside the core is called window and it is the space available for accommodating the primary and secondary winding.
- The window area is shared between the winding and their insulations.

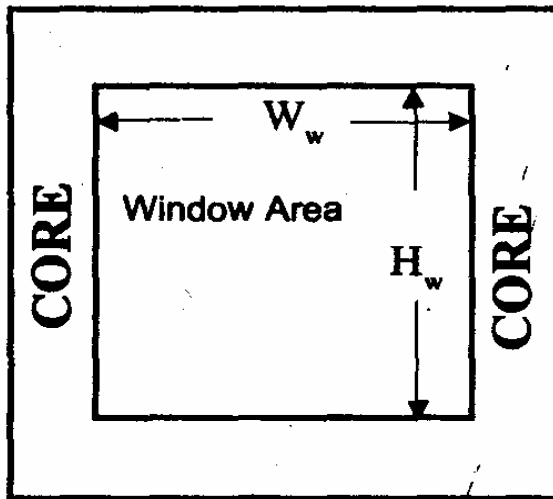
The simplified cross-section of core type and shell type single phase transformers



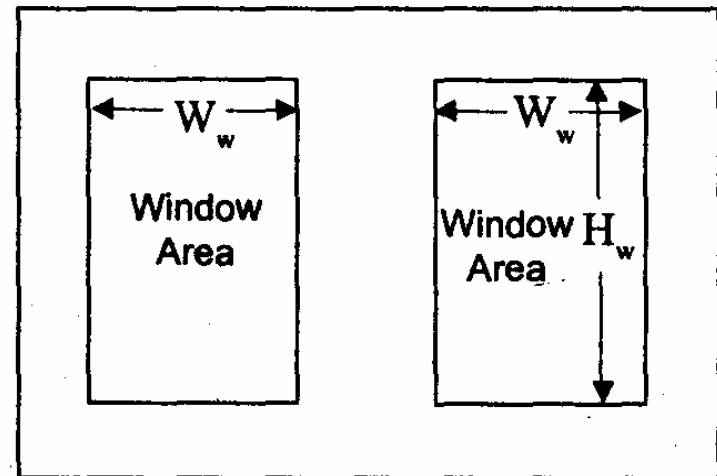
LVW - Low Voltage winding



HVW - High Voltage winding.



Core Type Transformer



Shell Type Transformer

Single phase core type transformer

The induced emf in a transformer, $E = 4.44 f \phi_m T$ Volts

Emf per turn, $E_t = E / T = 4.4 f \phi_m$ Volts

The window in single phase transformer contains one primary and one secondary winding.

The window space factor K_w is the ratio of conductor area in window to total area of window.

$$K_w = \frac{\text{Conductor area in window}}{\text{Total area of window}} = \frac{A_c}{A_w}$$

Conductor area in window, $A_c = K_w A_w$

The current density is same in both the windings. Therefore Current density =

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

Area of cross - section of primary conductor,

$$a_p = \frac{I_p}{\delta}$$

Area of cross - section of secondary conductor,

$$a_s = \frac{I_s}{\delta}$$

If we neglect magnetizing mmf then primary ampere turns is equal to secondary ampere turns. Therefore ampere turns,

$$AT = I_p T_p = I_s T_s$$

Total copper area in window,

A_c = Copper area of primary winding + Copper area of secondary winding

= (Number of primary turns x area of cross-section of primary conductor) + (Number of secondary turns x area of cross - section of secondary conductor)

$$\begin{aligned}
 &= T_p a_p + T_s a_s = T_p \frac{I_p}{\delta} + T_s \frac{I_s}{\delta} & \left(\because a_p = \frac{I_p}{\delta} \text{ and } a_s = \frac{I_s}{\delta} \right) \\
 &= \frac{1}{\delta} (T_p I_p + T_s I_s) = \frac{1}{\delta} (AT + AT) & (\because AT = I_p T_p = I_s T_s) \\
 &= \frac{2AT}{\delta}
 \end{aligned}$$

On equating the above equations, we get,

$$K_w A_w = 2AT/\delta$$

Therefore Ampere turns,

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

The kVA rating of single phase transformer is given by,

$$\begin{aligned}
 \text{kVA rating, } Q &= V_p I_p \times 10^{-3} \approx E_p I_p \times 10^{-3} \quad \left(\because E_p \approx V_p \right) \\
 &= \frac{E_p}{T_p} T_p I_p \times 10^{-3} \quad \left(\because E_t = \frac{E_p}{T_p} \text{ and } AT = T_p I_p \right) \\
 &= E_t AT \times 10^{-3}
 \end{aligned}$$

on substituting for E and AT from equations we get,

$$\begin{aligned}
 Q &= 4.44 f \phi_m \frac{K_w A_w \delta}{2} \times 10^{-3} \\
 &= 2.22 f \phi_m K_w A_w \delta \times 10^{-3} \quad \left(\because B_m = \frac{\phi_m}{A_i} \right) \\
 &= 2.22 f B_m A_i K_w A_w \delta \times 10^{-3}
 \end{aligned}$$

The above equation is the output equation of single phase core type transformer

Single phase shell type transformer

The induced emf in a transformer, $E = 4.44 f \phi_m T$ Volts

Emf per turn, $E_t = E / T = 4.4 f \phi_m$ Volts

The window in single phase transformer contains one primary and one secondary winding.

The window space factor K_w is the ratio of conductor area in window to total area of window.

$$K_w = \frac{\text{Conductor area in window}}{\text{Total area of window}} = \frac{A_c}{A_w}$$

Conductor area in window, $A_c = K_w A_w$

The current density is same in both the windings. Therefore Current

density =

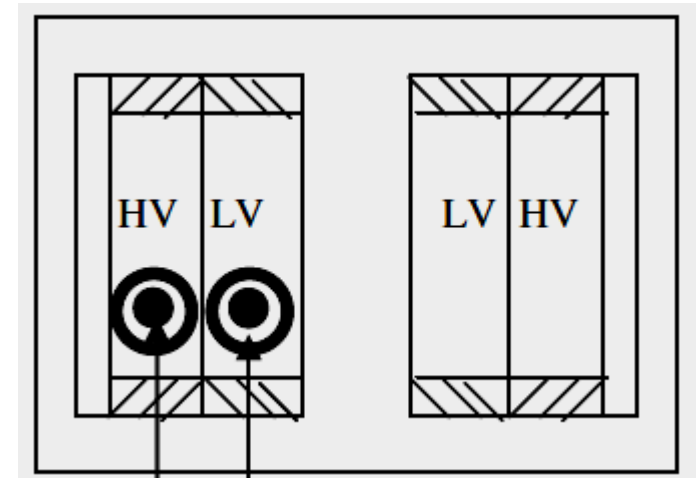
$$\delta = \frac{I_p}{a_p} = \frac{I_s}{a_s}$$

Area of X - section of primary conductor,

$$a_p = \frac{I_p}{\delta}$$

Area of X - section of secondary conductor,

$$a_s = \frac{I_s}{\delta}$$



If we neglect magnetizing mmf then primary ampere turns is equal to secondary ampere turns. Therefore ampere turns,

$$AT = I_p T_p = I_s T_s$$

Since there are two windows, it is sufficient to design one of the two windows as both the windows are symmetrical. Since the LV and HV windings are placed on the central leg, each window accommodates T_p and T_s turns of both primary and secondary windings

Copper area in window A_c

$$\begin{aligned}
 &= T_p a_p + T_s a_s = T_p \frac{I_p}{\delta} + T_s \frac{I_s}{\delta} & \left(\because a_p = \frac{I_p}{\delta} \text{ and } a_s = \frac{I_s}{\delta} \right) \\
 &= \frac{1}{\delta} (T_p I_p + T_s I_s) = \frac{1}{\delta} (AT + AT) & (\because AT = I_p T_p = I_s T_s) \\
 &= \frac{2AT}{\delta}
 \end{aligned}$$

On equating the above equations, we get,

$$K_w A_w = 2 AT / \delta$$

Therefore Ampere turns,

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

The kVA rating of single phase shell type transformer is given by,

$$\begin{aligned}
 \text{kVA rating, } Q &= V_p I_p \times 10^{-3} \approx E_p I_p \times 10^{-3} \quad \left(\because E_p \approx V_p \right) \\
 &= \frac{E_p}{T_p} T_p I_p \times 10^{-3} \quad \left(\because E_t = \frac{E_p}{T_p} \text{ and } AT = T_p I_p \right) \\
 &= E_t AT \times 10^{-3}
 \end{aligned}$$

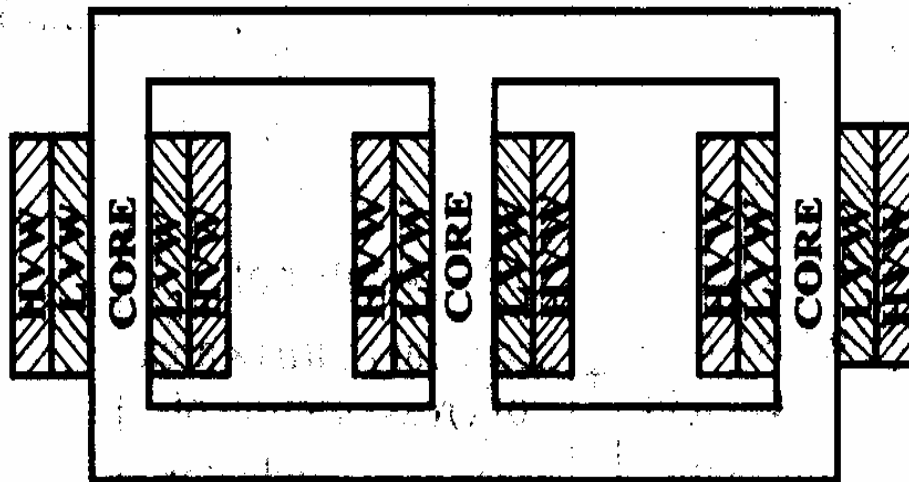
on substituting for E and AT from equations we get,

$$\begin{aligned}
 Q &= 4.44 f \phi_m \frac{K_w A_w \delta}{2} \times 10^{-3} \\
 &= 2.22 f \phi_m K_w A_w \delta \times 10^{-3} \quad \left(\because B_m = \frac{\phi_m}{A_i} \right) \\
 &= 2.22 f B_m A_i K_w A_w \delta \times 10^{-3}
 \end{aligned}$$

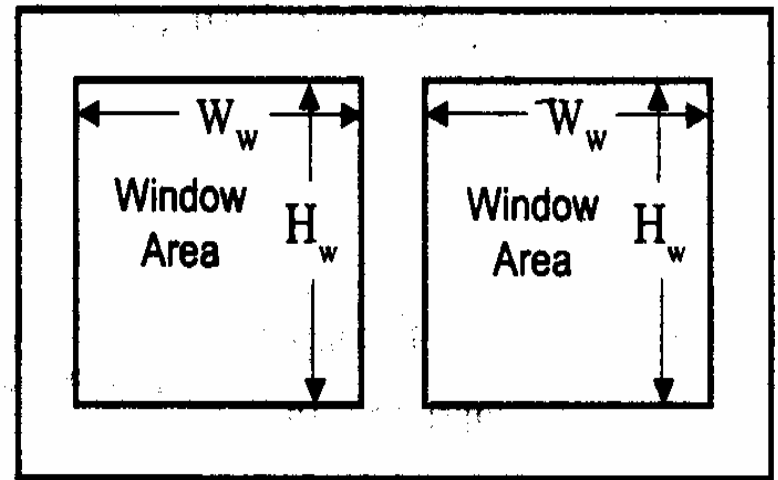
The above equation is the output equation of single phase shell type transformer

Three phase core type transformer

- Core type three phase transformer has three limbs and two windows as shown in figure.
- Each limb carries the low voltage and high voltage winding of a phase.



LVW - Low voltage winding



HVW - High voltage winding

The induced emf in a transformer, $E = 4.44 f \phi_m T$ Volts

Emf per turn, $E_t = E / T = 4.4 f \phi_m$ Volts

In case of three phase transformer, each window has two primary and two secondary windings.

window space factor K_w is
$$K_w = \frac{\text{Conductor area in window}}{\text{Total area of window}} = \frac{A_c}{A_w}$$

Conductor area in window, $A_c = K_w A_w$

The current density is same in both the windings. Therefore

Current density =
$$\delta = \frac{I_p}{a_p} = \frac{I_s}{a_s}$$

Area of cross - section of primary conductor,

$$a_p = \frac{I_p}{\delta}$$

Area of cross - section of secondary conductor,

$$a_s = \frac{I_s}{\delta}$$

If we neglect magnetizing mmf then primary ampere turns is equal to secondary ampere turns. Therefore ampere turns,

$$AT = I_p T_p = I_s T_s$$

Total copper area in window, $A_c = (2 \times \text{Number of primary turns} \times \text{area of cross-section of primary conductor}) + (2 \times \text{Number of secondary turns} \times \text{area of cross - section of secondary conductor})$

$$= 2 T_p a_p + 2 T_s a_s$$

$$= 2 T_p \frac{I_p}{\delta} + 2 T_s \frac{I_s}{\delta}$$

$$\left(\because a_p = \frac{I_p}{\delta} \text{ and } a_s = \frac{I_s}{\delta} \right)$$

$$= \frac{2}{\delta} (T_p I_p + T_s I_s)$$

$$= \frac{2}{\delta} (AT + AT)$$

$$\left(\because AT = I_p T_p = I_s T_s \right)$$

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

On equating the above equations, we get,

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

$$\therefore \text{Ampere-turn, } AT = \frac{K_w A_w \delta}{4}$$

The kVA rating of three phase transformer is given by,

$$\begin{aligned}
 Q &= 3 \times \text{Volt-ampere per phase} \times 10^{-3} = 3V_p I_p \times 10^{-3} \\
 &= 3E_p I_p \times 10^{-3} \quad (\because E_p \approx V_p) \\
 &= 3 \times \frac{E_p}{T_p} \times T_p I_p \times 10^{-3} \quad \left(\because E_t = \frac{E_p}{T_p} \text{ and } AT = T_p I_p \right) \\
 &= 3 E_t AT \times 10^{-3}
 \end{aligned}$$

on substituting for E and AT from equations we get,

$$\begin{aligned}
 Q &= 3 \times 4.44 f \phi_m \times \frac{K_w A_w \delta}{4} \times 10^{-3} \\
 &= 3.33 f \phi_m K_w A_w \delta \times 10^{-3} \quad \left(\because B_m = \frac{\phi_m}{A_i} \right) \\
 &= 3.33 f B_m A_i K_w A_w \delta \times 10^{-3}
 \end{aligned}$$

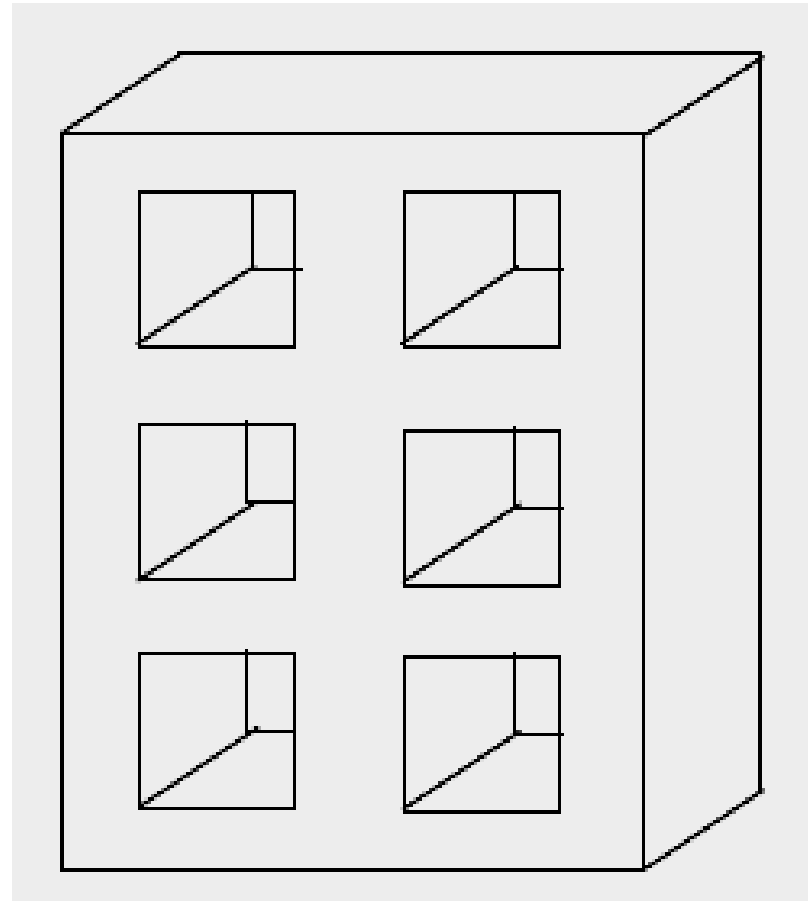
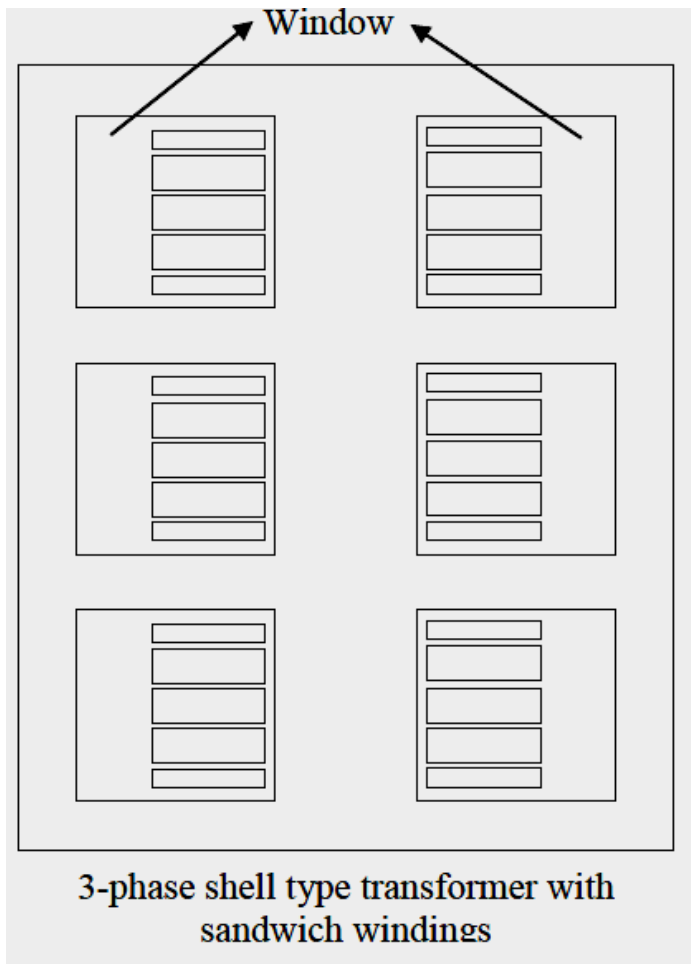
The above equation is the output equation of three phase transformer

Three phase shell type transformer

Rating of the transformer in

$$\begin{aligned} Q &= V_p I_p \times 10^{-3} = E_p I_p \times 10^{-3} \text{ kVA} \\ &= 4.44 \Phi_m f T_p \times I_p \times 10^{-3} \text{ kVA} \end{aligned}$$

Since there are six windows, it is sufficient to design one of the six windows, as all the windows are symmetrical. Since each central leg carries the LV and HV windings of one phase, each window carries windings of only one phase.



Copper area in window $A_c =$

$$\begin{aligned} &= T_p a_p + T_s a_s = T_p \frac{I_p}{\delta} + T_s \frac{I_s}{\delta} & \left(\because a_p = \frac{I_p}{\delta} \text{ and } a_s = \frac{I_s}{\delta} \right) \\ &= \frac{1}{\delta} (T_p I_p + T_s I_s) = \frac{1}{\delta} (AT + AT) & (\because AT = I_p T_p = I_s T_s) \\ &= \frac{2AT}{\delta} \end{aligned}$$

On equating the above equations, we get,

$$K_w A_w = 2AT/\delta$$

Therefore Ampere turns,

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

on substituting AT in kVA rating,

$$Q = 3 \times 4.44 A_i B_m f \times (A_w K_w \delta / 2) \times 10^{-3} \text{ kVA}$$

$$Q = 6.66 f \delta A_i B_m A_w K_w \times 10^{-3} \text{ kVA}$$

Output equation of transformer

Single phase core type & shell type transformer :-

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

Three Phase core type transformer :-

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

Three Phase shell type transformer :-

$$Q = 6.66 f B_m \delta K_w A_w A_i \cdot 10^{-3} \text{ kVA}$$

Usual values of flux density

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

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

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

Usual values of current density

This depends upon cooling method employed

Natural Cooling: 1.5---2.3 A/mm²

AN Air Natural cooling

ON Oil Natural cooling

OFN Oil Forced circulated with Natural air cooling

Forced Cooling : 2.2---4.0 A/mm²

AB Air Blast cooling

OB Oil Blast cooling

OFB Oil Forced circulated with air Blast cooling

Water Cooling: 5.0 ---6.0 A/mm²

OW Oil immersed with circulated Water cooling

OFW Oil Forced with circulated Water cooling

Emf per turn equation

To solve the output equation,

$kVA = 2.22 \text{ or } 3.33 \text{ or } 6.66 f \delta A_i B_m A_w K_w \times 10^{-3}$ having two unknowns A_i and A_w , volt per turn equation is considered.

Rating of the transformer per phase

$$\begin{aligned} Q &= V_p I_p \times 10^{-3} = E_p I_p \times 10^{-3} \text{ kVA} & (V_p \approx E_p) \\ &= 4.44 \Phi_m f T_p I_p \times 10^{-3} \end{aligned}$$

The term Φ_m is called the magnetic loading and $I_1 T_1$ is called the electric loading. The required kVA can be obtained by selecting a higher value of Φ_m and a lesser of $I_p T_p$ or vice-versa.

As the magnetic loading increases, flux density and hence the core loss increases and the efficiency of operation decreases. Similarly as the electric loading increases, number of turns, resistance and hence the copper loss increases. This leads to reduced efficiency of operation. It is clear that there is no advantage by the selection of higher values of $I_p T_p$ or Φ_m . For an economical design they must be selected in certain proportion. Let, ratio of specific magnetic and electric loading be,

$$k = \frac{\Phi_m}{AT}$$

Considering the primary voltage and current per phase

kVA rating of transformer:

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

$$= 4.44 f \phi_m T_p I_p \times 10^{-3} \quad (\because V_p \approx E_p = 4.44 f \phi_m T_p)$$

$$= 4.44 f \phi_m AT \times 10^{-3} \quad (\because T_p I_p = AT)$$

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

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

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

- We know that Emf per turn,

$$E_t = 4.44 f \phi_m$$

- On substituting for Φ_m from equation we get,

$$E_t = 4.44 f \sqrt{\frac{Q_r \times 10^3}{4.44 f}} = \sqrt{4.44 f r \times 10^3} \sqrt{Q} = K \sqrt{Q}$$

$$\text{where, } K = \sqrt{4.44 f r \times 10^3} = \sqrt{4.44 f \times \frac{\phi_m}{AT} \times 10^3}$$

- From the above equation we can say that the emf per turn is directly proportional to K.
- The value of K depends on the type, service condition and method of construction of transformer.

The value of K for different types of transformers is listed in table below.

Transformer type	K
Single phase shell type	1.0 to 1.2
Single phase core type	0.75 to 0.85
Three phase shell type	1.3
Three phase core type, distribution transformer	0.45
Three phase core type, power transformer	0.6 to 0.7

Design of Cores

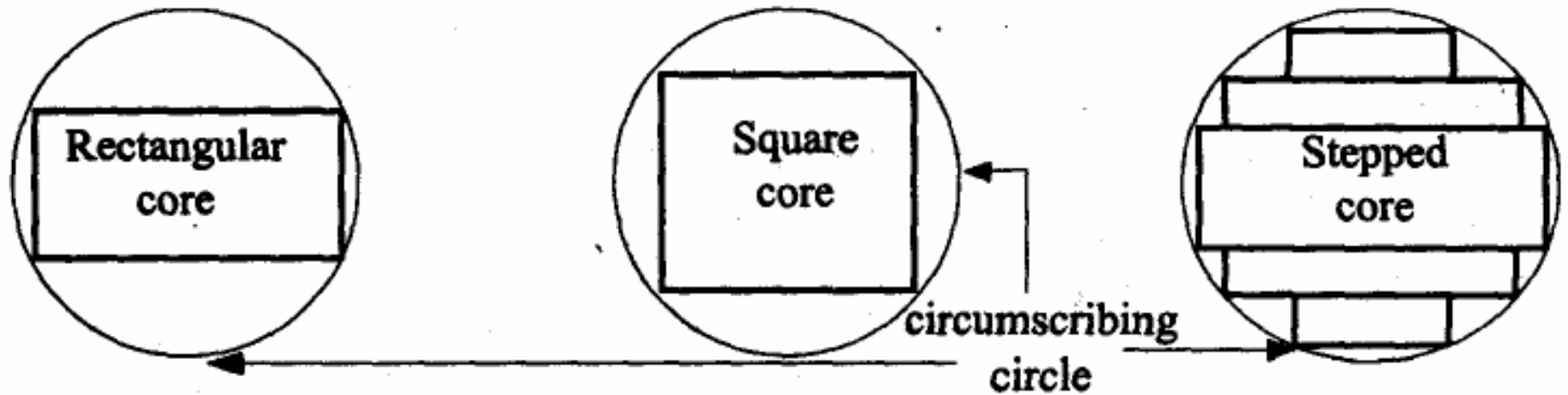
Rectangular core: It is used for core type distribution transformer and small power transformer for moderate and low voltages and shell type transformers.

In core type transformer the ratio of depth to width of core varies between 1.4 to 2.

In shell type transformer width of central limb is 2 to 3 times the depth of core.

Square and stepped cores: For high voltage transformers, where circular coils are required, square and stepped cores are used.

Square and stepped core



- In square cores the diameter of the circumscribing circle is larger than the diameter of stepped cores of same area of cross-section.
- Thus when stepped cores are used the length of mean turn of winding is reduced with consequent reduction in both cost of copper and copper loss.
- However with larger number of steps a large number of different sizes of laminations have to be used.
- This results in higher labor charges for shearing and assembling different types of laminations.

Square Core

Let d = diameter of circumscribing circle

Also, d = diagonal of the square core and a = side of square

Diameter of circumscribing circle,

$$d = \sqrt{a^2 + a^2} = \sqrt{2 a^2} = \sqrt{2} a$$

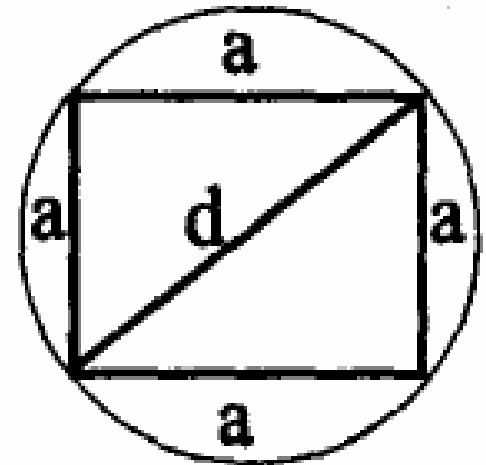
Therefore Side of square,

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

Gross core area, A_{gj} = area of square = a^2

$$a^2 = (d / \sqrt{2})^2 = 0.5 d^2$$

Let stacking factor, $S_f = 0.9$



Square Core

$$\begin{aligned}\text{Net core area, } A_i &= \text{Stacking factor} \times \text{Gross core area} \\ &= 0.9 \times 0.5 d^2 = 0.45 d^2\end{aligned}$$

Area of circumscribing circle,

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

$$\text{The ratio, } \frac{\text{Net core area}}{\text{Area of circumscribing circle}} = \frac{0.45 d^2}{(\pi/4) d^2} = 0.58$$

$$\text{The ratio, } \frac{\text{Gross core area}}{\text{Area of circumscribing circle}} = \frac{0.5 d^2}{(\pi/4) d^2} = 0.64$$

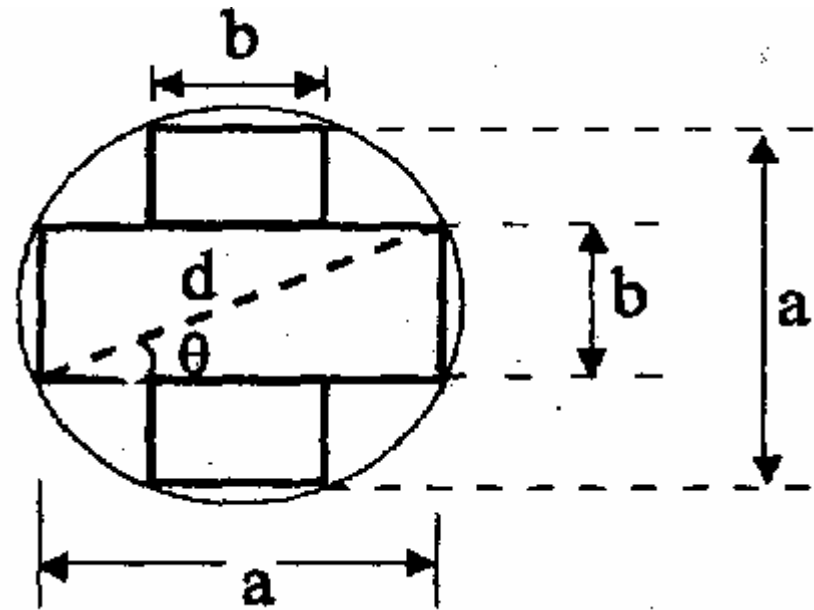
Two Stepped Core for Cruciform Core

a = Length of the rectangle

b = Breadth of the rectangle

d = Diameter of the circumscribing circle

Also, d = Diagonal of the rectangle



θ = Angle between the diagonal and length of the rectangle.

The maximum core area for a given d is obtained when θ is maximum value.

Hence differentiate A_{gi} with respect to θ and equate to zero to solve for maximum value of θ .

From figure we get,

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

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

$$A_{gi} = ab + \left(\frac{a-b}{2}\right)b + \left(\frac{a-b}{2}\right)b = ab + \frac{2(a-b)}{2}b$$

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

On substituting for a and b in above equation

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

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

$$= d^2 \sin 2\theta - d^2 \sin^2 \theta$$

To get maximum value of θ , differentiate A_{gi} with respect to θ , and equate to zero, i.e., $\frac{d}{d\theta} A_{gi} = 0$

$$\frac{d}{d\theta} A_{gi} = d^2 \cos 2\theta \times 2 - d^2 2 \sin\theta \cos\theta = 0$$

$$\tan 2\theta = 2 \qquad \theta = \frac{1}{2} \tan^{-1} 2 = 31.72^\circ$$

When $\theta = 31.72^\circ$ the dimensions of the core (a & b) will give the maximum area for core for a specified 'd'.

$$\begin{aligned} a &= d \cos\theta \\ &= d \cos 31.72^\circ \\ &= 0.85d \end{aligned}$$

$$\begin{aligned} b &= d \sin\theta \\ &= d \sin 31.72^\circ \\ &= 0.53d \end{aligned}$$

On substituting the above values of a & b

$$A_{gi} = 2ab - b^2 = 0.618 d^2$$

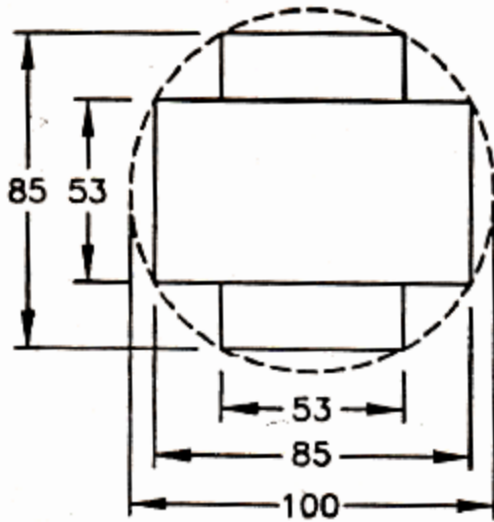
Let stacking factor, $S_f = 0.9$

Net core-area, $A_i = \text{Stacking factor} \times \text{Gross core area}$
 $= 0.9 \times 0.618 d^2 = 0.56 d^2$

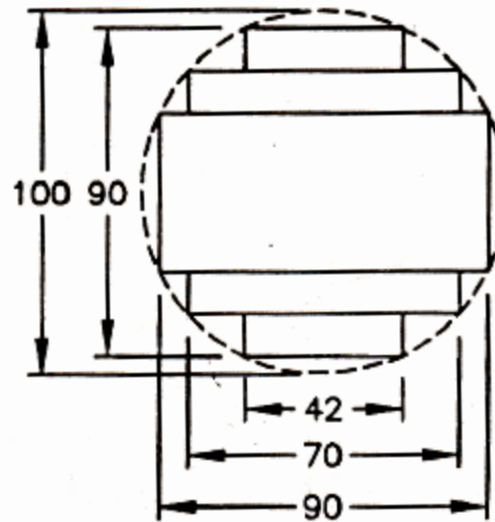
The ratio, $\frac{\text{Net core area}}{\text{Area of circumscribing circle}} = \frac{0.56d^2}{(\pi/4) d^2} = 0.71$

The ratio, $\frac{\text{Gross core area}}{\text{Area of circumscribing circle}} = \frac{0.618d^2}{(\pi/4) d^2} = 0.79$

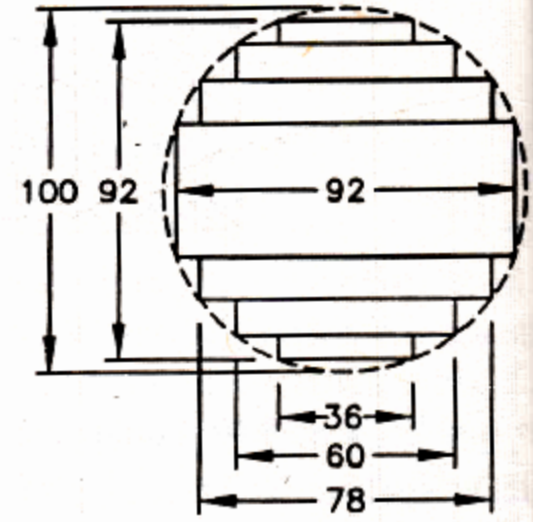
Cross-section and dimensions of Stepped cores



(a) 2-stepped (cruciform)



(b) 3-stepped



(c) 4-stepped

<i>Area %age of circumscribing circle</i>	<i>Square</i>	<i>Cruciform</i>	<i>Three stepped</i>	<i>Four Stepped</i>
Gross core area, A_{gi}	64	79	84	87
Net core area, A_i	58	71	75	78
Net core area $A_i = k_c d^2$, k_c	0.45	0.56	0.6	0.62

Window Space Factor: It is the ratio of copper area in the window to the total window area.

$K_w = 10/(30+kV)$	for transformer rating 50 to 200kVA
$K_w = 12/(30+kV)$	for rating about 1000 kVA
$K_w = 8/(30+kV)$	for rating about 20 kVA

Window dimensions:

The area of window depend upon total conductor area and window space factor.

$$\begin{aligned}\text{Area of window } A_w &= \text{total conductor area} / \text{window space factor} \\ &= 2.a_p T_p / K_w \text{ for 1-ph transformer} \\ &= 4.a_p T_p / K_w \text{ for 3-ph transformer}\end{aligned}$$

$$A_w = \text{height of window} \times \text{width of window} = H_w \times W_w$$

The ratio of height to width of window, H_w / W_w is b/w 2 to 4.

Design of Yoke: The section of yoke can either be taken as rectangular or it may be stepped.

In rectangular section yokes,
depth of the yoke = depth of core

area of yoke $A_y = D_y \times H_y$

$D_y = \text{depth of yoke} = \text{width of largest core stamping}$
 $= a$

$A_y = 1.15 \text{ to } 1.25 \text{ of } A_{gi} \text{ for hot rolled steel}$
 $= A_{gi} \text{ for CRGO}$

Overall Dimensions

d = diameter of circumscribing circle

D = distance b/w centers of adjacent limbs

H = overall height

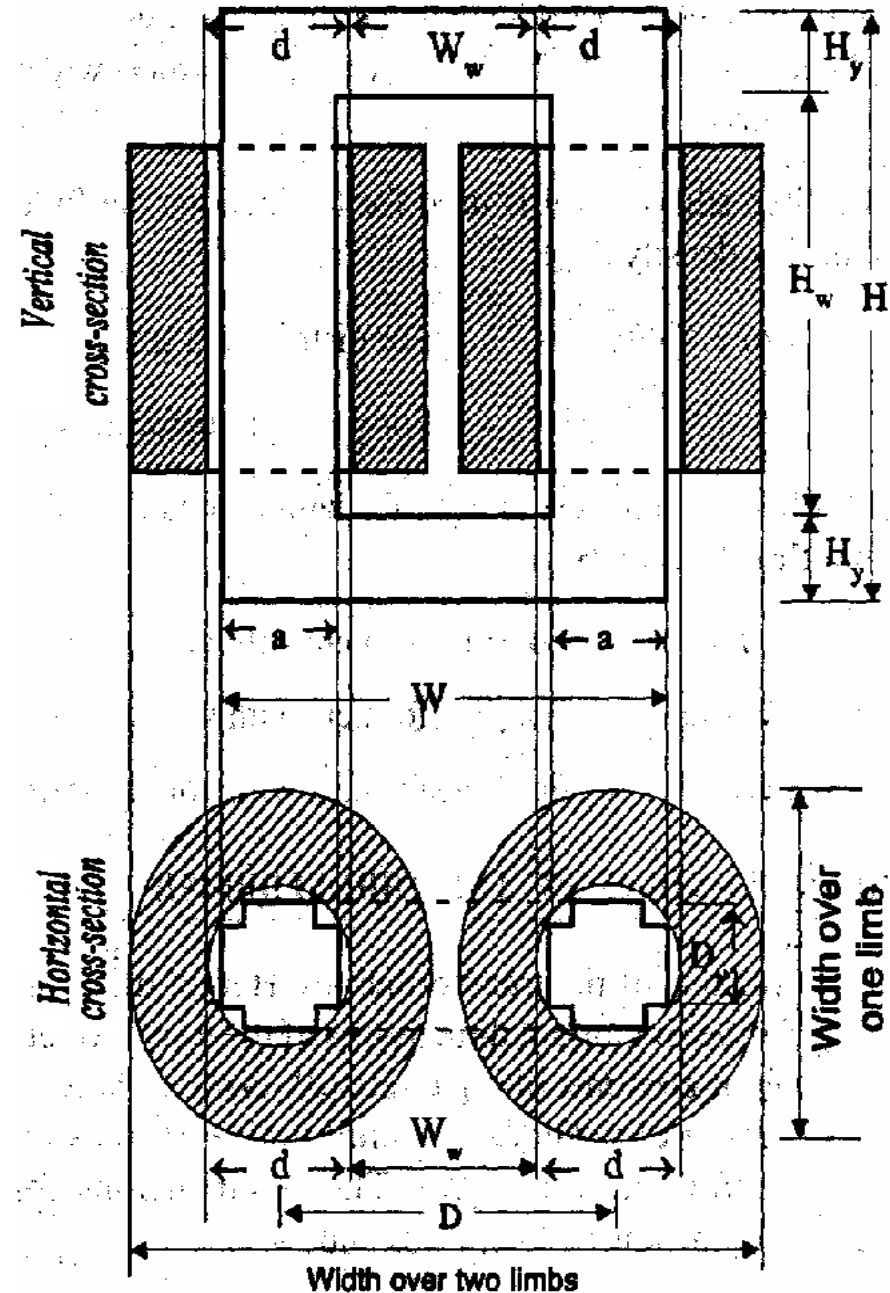
W = length of yoke

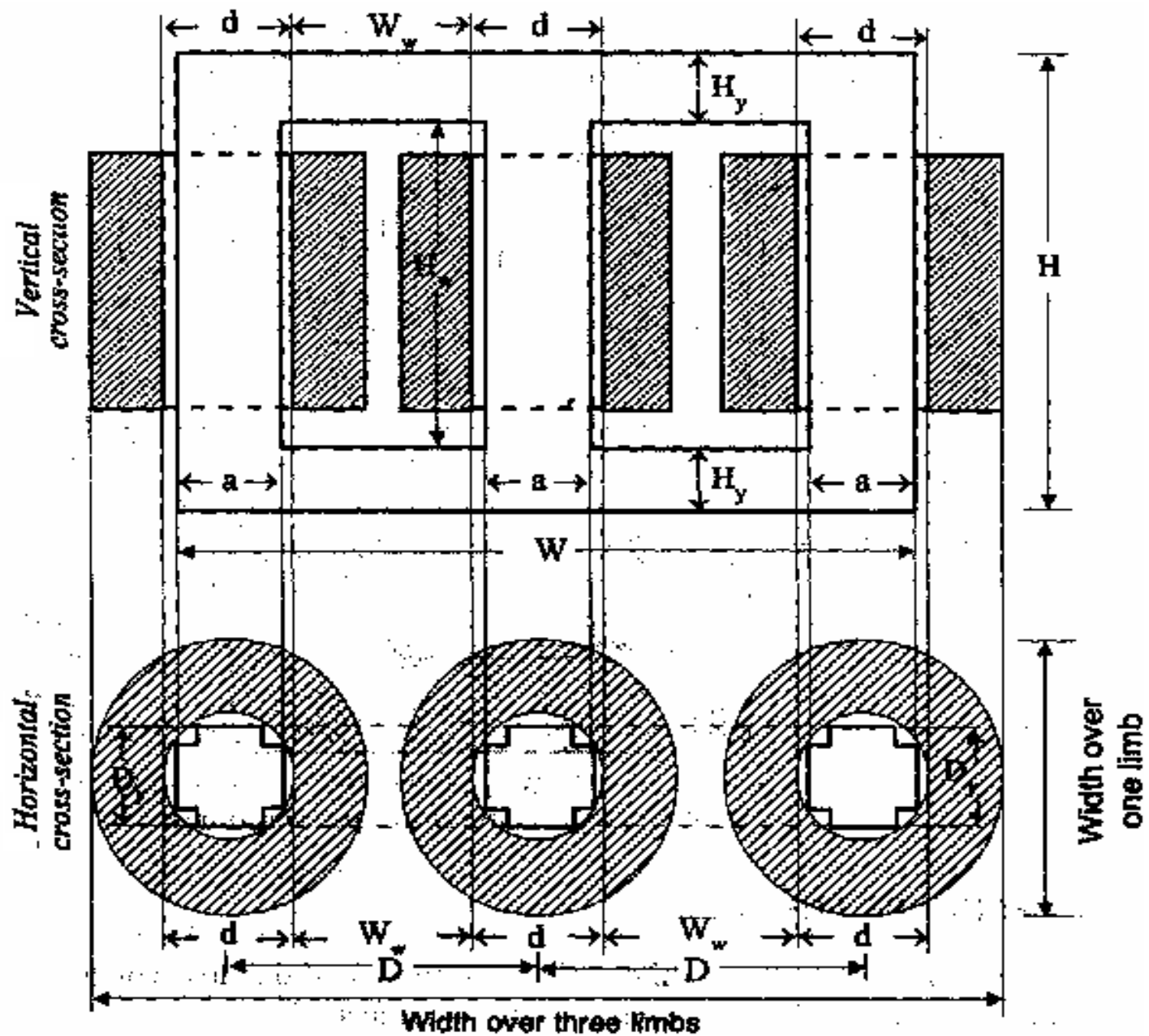
H_w = height of window

W_w = width of window

a = width of largest stamping

H_y = height of yoke





1-Φ Core Type Transformer

$$D = d + W_w$$

$$D_y = a$$

$$H = H_w + 2H_y$$

$$W = D + a$$

Width over two limbs = D + outer diameter of hv winding

Width over one limb = outer diameter of hv winding

3-Φ Core Type Transformer

$$D = d + W_w, \quad D_y = a$$

$$H = H_w + 2H_y$$

$$W = 2D + a$$

Width over three limbs = $2*D$ + outer diameter of hv winding

Width over one limb = outer diameter of hv winding

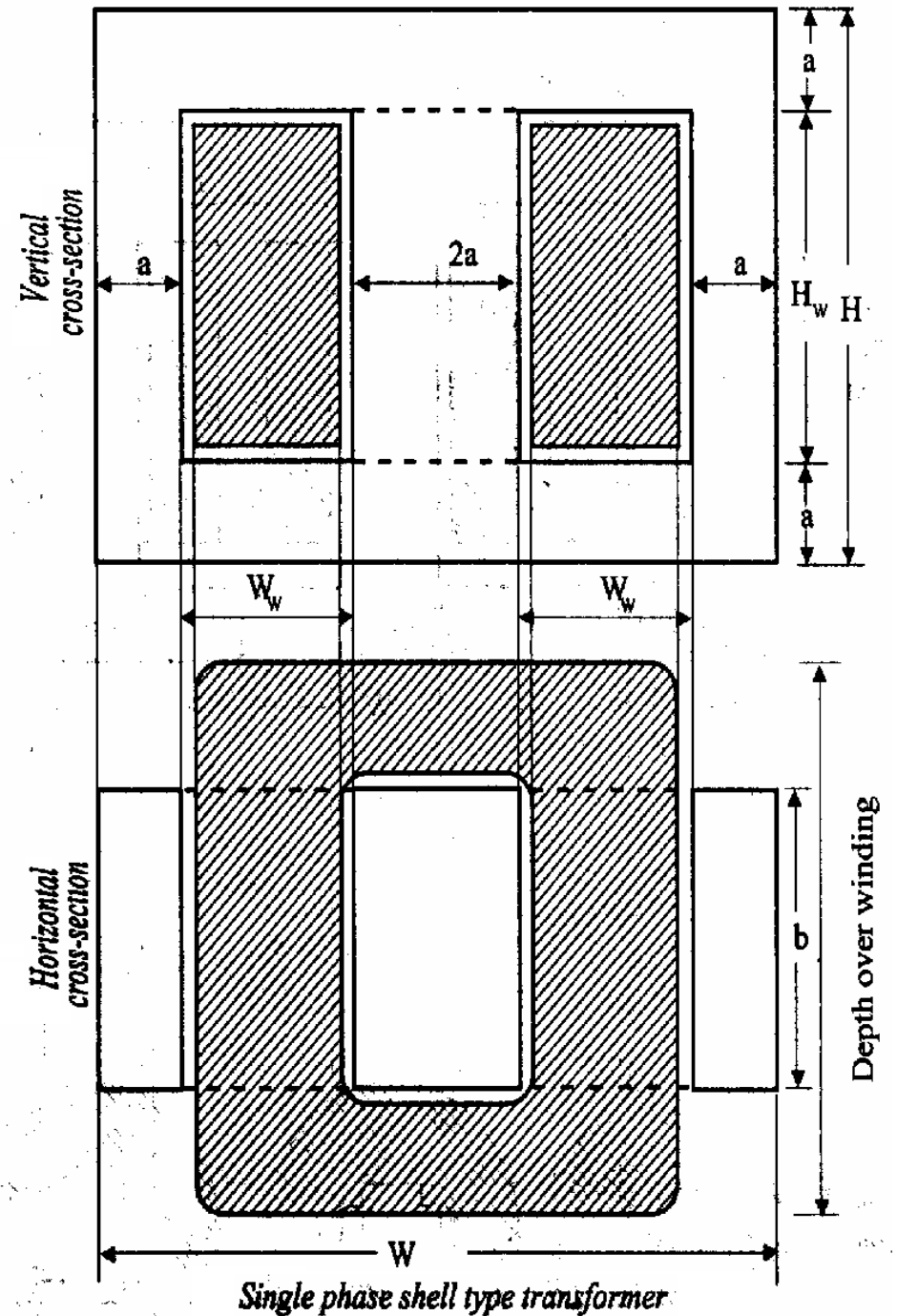
1- Φ Shell Type Transformer

$$D_y = b$$

$$H_y = a$$

$$W = 2W_w + 4a$$

$$H = H_w + 2a$$



Estimation of no of turns :

Primary no of turns $T_p = V_p / E_t$

Secondary no of turns $T_s = V_s / E_t$

Estimation of sectional area of windings

Primary current $I_p = Q \cdot 10^{-3} / 3V_p$

Secondary current $I_s = Q \cdot 10^{-3} / 3V_s$

Sectional area of primary winding $a_p = I_p / \delta$

Sectional area of primary winding $a_s = I_s / \delta$

Resistance of Transformer

Resistance of the primary winding/phase $r_p = (\rho L_{mt}) T_p / a_p$ ohm

Mean length of turn of the primary winding $L_{mt_p} = \pi \times \text{mean diameter of the primary winding}$

Resistance of the secondary winding/phase $r_s = (\rho L_{mt}) T_s / a_s$ ohm

Mean length of turn of the Secondary winding $L_{mt_s} = \pi \times \text{mean diameter of the secondary winding}$

Resistance of the transformer referred to primary / phase

$$R_p = r_p + r_s' = r_p + r_s (T_p/T_s)$$

Resistance of the transformer referred to secondary / phase

$$R_s = r_s + r_p' = r_s + r_p (T_s/T_p)$$

Reactance of Transformer

Useful flux: It is the flux that links with both primary and secondary windings and is responsible in transferring the energy Electro-magnetically from primary to secondary side. The path of the useful flux is in the magnetic core.

Leakage flux: It is the flux that links only with the primary or secondary winding and is responsible in imparting inductance to the windings. The path of the leakage flux depends on the geometrical configuration of the coils and the neighboring iron masses.

If x_p and x_s are the leakage reactances of the primary and secondary windings, then the total leakage reactance of the transformer referred to primary winding

$$X_p = x_p + x_s' = x_p + x_s (T_p/T_s)^2$$

and total leakage reactance of the transformer referred to primary winding

$$X_s = x_s + x_p' = x_s + x_p (T_s/T_p)^2$$

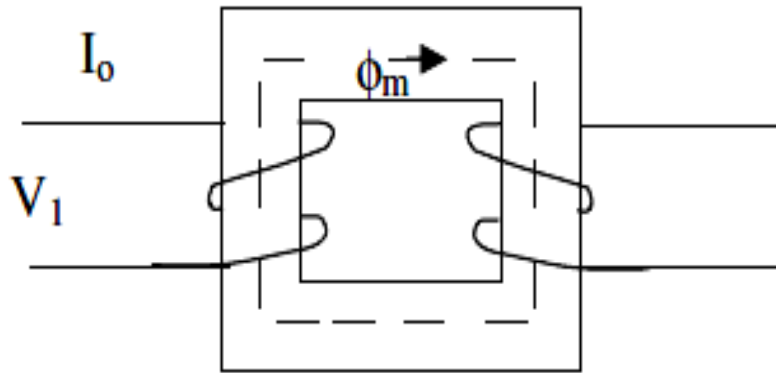
Voltage Regulation

$$\begin{aligned} V.R. &= \frac{I_s R_s \cos \Phi_2 \pm I_s X_s \sin \Phi_2}{E_s} * 100 \\ &= \frac{R_s \cos \Phi_2 * 100}{E_s / I_s} \pm \frac{X_s \sin \Phi_2 * 100}{E_s / I_s} \\ &= \%R_s \cos \Phi_2 \pm \%X_s \sin \Phi_2 \end{aligned}$$

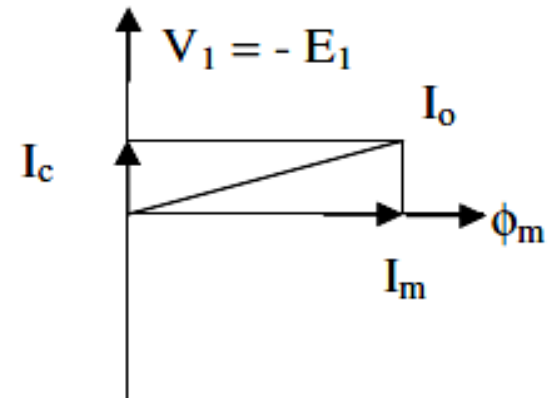
No-load current of transformer

The no-load current I_0 is the vectorial sum of the magnetizing current I_m and core loss or working component current I_c . [Function of I_m is to produce flux Φ_m in the magnetic circuit and the function of I_c is to satisfy the no load losses of the transformer].

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



Transformer under no-load condition



Vector diagram of Transformer under no-load condition

No load input to the transformer/ph = $V_1 I_0 \cos \phi_0 = V_1 I_c$

No load losses as the output is zero and input = output + losses.

Since the copper loss under no load condition is almost negligible, the no load losses can entirely be taken as due to core loss only. Thus the core loss component of the no load current

$$I_c = \text{core loss} / V_1 \quad \text{for single phase transformers}$$

$$I_c = \text{core loss} / 3V_1 \quad \text{for three phase transformers}$$

$$\text{RMS value of magnetizing current } I_m = \frac{\text{Magnetizing ampere turns (Max value)}}{\sqrt{2} T_1}$$

The magnetic circuit of a transformer consists of both iron and air path. The iron path is due to legs and yokes and air path is due to the unavoidable joints created by the core composed of different shaped stampings. If all the joints are assumed to be equivalent to an air gap of length l_g , then the total ampere turns for the transformer magnetic circuit is equal to $AT_{for\ iron} + 800,000l_gB_m$.

$$AT_o = AT_{for\ iron} + 800,000l_gB_m$$

$$AT_{for\ iron} = 2\ at_c\ l_c + 2at_y\ l_y \text{ for single phase transformer}$$

$$AT_{for\ iron} = 3\ at_c\ l_c + 2at_y\ l_y \text{ for three phase transformer}$$

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

at_c, at_y = mmf/m for flux densities in core and yoke respectively

$$I_m = \frac{AT_{\text{for iron}} + 800,000 l_g B_m}{\sqrt{2} T_1}$$

1. In case of a transformer of normal design, the no load current will generally be less than about 2% of the full load current.

2. No load power factor $\cos\phi_o = I_c/I_o$ and will be around 0.2.

3. **Transformer copper losses:**

a) The primary copper loss at no load is negligible as I_o is very less.

b) The secondary copper loss is zero at no load, as no current flows in the secondary winding at no load.

4. **Core or iron loss:**

Total core loss = core loss in legs + core loss in yokes.

Core loss in leg = loss/kg in leg * weight of leg in kg

= loss / kg in leg * volume of the leg ($A_l * H_w$) * density of steel or iron used

Core loss in yoke = loss/kg in Yoke * volume of yoke (A_y * mean length of the yoke) * density of iron used

Temperature rise of Transformer

- The losses developed in the transformer cores and windings are converted into thermal energy and cause heating of corresponding transformer parts.
- The heat dissipation in transformer occurs by Conduction, Convection and Radiation.

The paths of heat flow in transformer are the following

1. From internal most heated spots of a given part (of core or winding) to their outer surface in contact with the oil.
2. From the outer surface of a transformer part to the oil that cools it.
3. From the oil to the walls of a cooler, eg. Wall of tank.
4. From the walls of the cooler to the cooling medium air or water.

- In the path 1 mentioned above heat is transferred by conduction.
- In the path 2 and 3 mentioned above heat is transferred by convection of the oil.
- In path 4 the heat is dissipated by both convection and radiation.

In small capacity transformers the surrounding air will be in a position to cool the transformer effectively and keeps the temperature rise well within the permissible limits.

As the capacity of the transformer increases, the losses and the temperature rise increases. In order to keep the temperature rise within limits, air may have to be blown over the transformer. This is not advisable as the atmospheric air containing moisture, oil particles etc., may affect the insulation. To overcome the problem of atmospheric hazards, the transformer is placed in a steel tank filled with oil.

Further as the capacity of the transformer increases, the increased losses demands a higher dissipating area of the tank or a bigger sized tank. This calls for more space, more volume of oil and increases the cost and transportation problems. To overcome these difficulties, the dissipating area is to be increased by artificial means with out increasing the size of the tank. The dissipating area can be increased by

1. fitting fins to the tank walls
2. fitting tubes to the tank
3. using corrugated tank
4. using auxiliary radiator tanks

Since the fins are not effective in dissipating heat and corrugated tank involves constructional difficulties, they are not much used now a days. The tank with tubes are much used in practice.

Plain Walled Tanks

Heat goes dissipated to the atmosphere from tank by radiation and convection. It has been found by experiment that a plain tank surface dissipate 6.0W and 6.5W/m²–°C by radiation and convection respectively. Thus a total loss dissipation is 12.5W/m²–°C.

$$\text{Temp rise } \theta = \frac{\text{total loss}}{\text{specific heat dissipation} * \text{surface}} = \frac{P_i + P_c}{12.5 S_t}$$

S_t = Heat dissipating surface of tank

Design of Tank with Tubes

If the temperature rise of plain tank exceeds the permissible limit of about 50 degree centigrade, then cooling tubes are to be added to reduce the temperature rise. With the tubes connected to the tank, dissipation due to radiation from a part of the tank surface screened by the tubes is zero. So there is no change in surface as far as dissipation of heat due to radiation is concerned. Because the oil when get heated up moves up and cold oil down, circulation of oil in the tubes will be more. Obviously, this circulation of oil increases the heat dissipation by convection about 35%.

Let dissipating surface of the tank = S_t

It will dissipate $12.5 S_t \text{ W/}^\circ\text{C}$

Let the area of tubes = xS_t

*Loss dissipated by tubes by convection = $1.35 * 6.5 xS_t = 8.8 xS_t \text{ W/}^\circ\text{C}$*

Total loss dissipated by tank & tubes = $12.5 S_t + 8.8 xS_t = S_t(12.5 + 8.8 x) \text{ W/}^\circ\text{C}$

Total area of tank walls and tubes = $S_t + xS_t = S_t (1 + x)$

$$\text{Loss dissipated} = \frac{(12.5 + 8.8x)}{x + 1} \text{ W/m}^2 - ^\circ\text{C}$$

$$\text{Temperature Rise with tubes } \theta = \frac{P_i + P_c}{S_t(12.5 + 8.8x)}$$

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

$$\text{Total area of tubes} = \frac{1}{8.8} \left(\frac{P_i + P_e}{\theta} - 12.5.S_t \right)$$

Let l_t and d_t be the length and diameter of each tube

$$\text{Area of each tube} = \pi d_t l_t$$

$$\text{Number of tubes } n_t = \frac{1}{8.8\pi d_t l_t} \left(\frac{P_i + P_e}{\theta} - 12.5.S_t \right)$$

The diameter of tubes, normally used, is 50 mm and they are spaced at 75 mm

Cooling of Transformer

The coolants used in transformers are air and oil.

Transformers using air as coolant are called Dry type transformers while transformers which use oil as coolant are called Oil immersed transformers.

Methods of Cooling of Transformers: the choice of cooling method depends upon the size, type of application and the type of conditions of installation sites.

The symbols designated these methods depend upon medium of cooling used and type of circulation employed.

Medium:- Air-A, Gas-G, Oil-O, Water-W, Solid insulation-S

Circulation:- Natural-N, Forced-F

Cooling of Dry-type transformer

Air Natural (AN), Air Blast (AB)

Cooling of oil immersed transformer

Oil Natural (ON)

Oil Natural Air Forced (ONAF)

Oil Natural Water Forced (ONWF)

Forced Circulation of Oil (OF)

- i. Oil Forced Air Natural (OFAN)
- ii. Oil Forced Air Forced (OFAF)
- iii. Oil Forced Water Forced (OFWF)