2.1. Design difference between distribution transformer and power transformer

(a) Distribution transformer

- Standard ratings 10, 16, 25, 63, 100, 160, 200, 250, 315, 400, 500, 630, 1000, 1250, 1600, 2000, 2500 kVA for 11 kV distribution system and 100, 160, 200, 315, 400, 500, 630, 1000, 1250, 1600, 2000, 2500 kVA for 33 kV system.
- Used in electric power distribution system.
- Operates at light loads during major parts of the day.
- Very high load fluctuation.
- Designed for maximum efficiency at 60-70% of full load.
- More energy is lost in iron loss compared to copper loss throughout the day so designed for minimum iron loss.
- Designed for small value of leakage reactance for voltage regulation purpose.
- Designed to operate for flux density below to the saturation point of the B-H curve.
- Usually primary winding is designed for delta connections and secondary winding is designed for star connection.
- Generally oil natural circulation cooling method is used to maintain the temperature of the transformer.
- Smaller in size.

(b) Power transformer

- Standard ratings above 2500 kVA and up to 1000 MVA for above 30 kV and up to 1500 kV.
- Used at power generating power stations and transmission substation.
- Operates at nearly full load during major parts of the day.
- Load fluctuations is very less.
- Designed for maximum efficiency at full load.
- More energy is lost in copper loss compared to iron loss throughout the day so designed for minimum copper loss.
- Designed for comparatively large value of leakage reactance for short circuit current limiting purpose.
- Designed to operate for flux density near to the saturation point of the B-H curve.
- Usually primary winding is designed for star connections and secondary winding is designed for delta connection.
- Forced circulation of oil is used to maintain the temperature of the transformer.
- Larger in size.

2.2. Design difference between core type transformer and shell type transformer

(a) Core type transformer

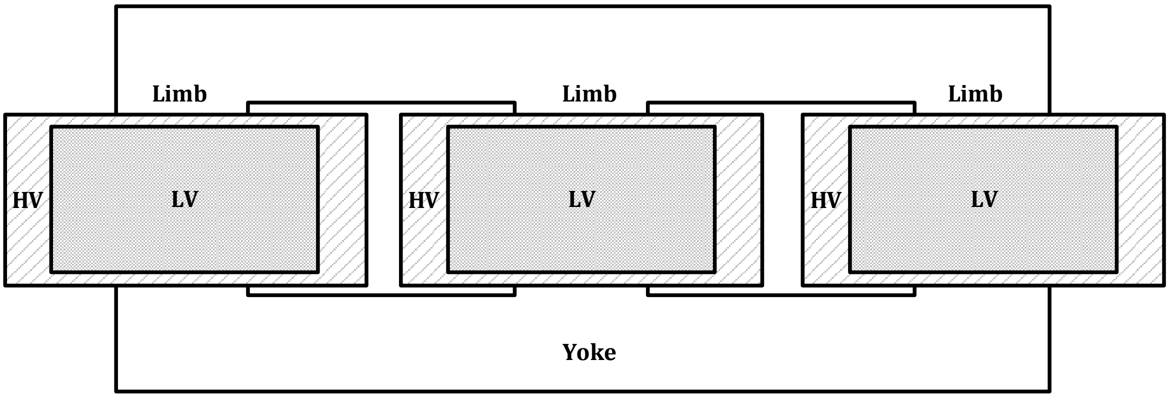

Figure 2. 1 Three phase core type transformer

- Limbs are surrounded by the windings.
- No separate flux return path is essential.
- All limb carries equal flux.
- Laminated core is built to form rectangular frame.
- Winding has poor mechanical strength because they are not supported or braced.
- Beyond one level it is not possible to reduce leakage because high voltage and low voltage winding cannot be subdivided to great extent.
- Limbs are surrounded by the windings so cooling is batter in winding than limb.
- Permits easier assemble of parts and insulation of winding.
- Easy to dismantle for maintenance or repair.
- Much simpler in design.

(b) Shell type transformer

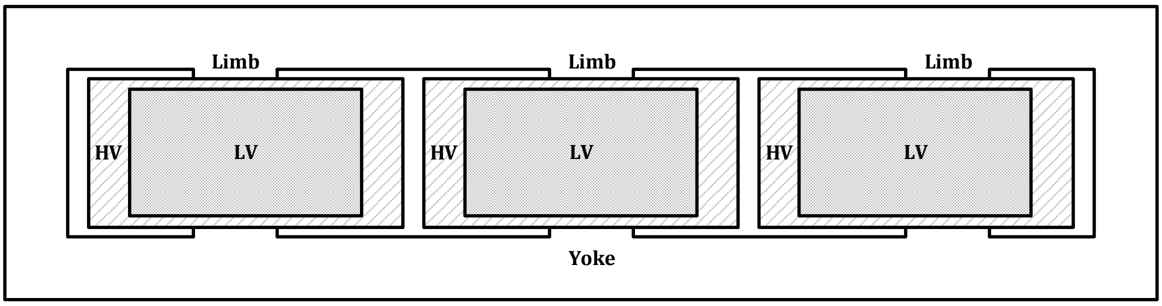

Figure 2. 2 Three phase shell type transformer

- Windings are surrounded by the limbs.
- Separate flux return paths is essential.
- Central limb carries whole flux and side limb carries half of the total flux.
- Laminated core is built to form rectangular frame.
- Winding has excessive mechanical strength because they are supported or braced.

- It is possible to reduce leakage because high voltage and low voltage winding can be subdivided by using sandwich coil.
- Windings are surrounded by the limbs so cooling is batter in core than winding.
- Great difficulty to assemble parts and insulation of winding.
- Difficult to dismantle for maintenance or repair.
- More complex in design.

2.3. Output equation of 3-phase transformer

- Output equation of transformer is the mathematical expression relating kVA rating with main dimension.
- In 3-phase transformer one window contains half of high voltage (HV) winding and half of low voltage (LV) winding of two consecutive phase. Two such windows forms entire assembly.

  Let,

  Q = Output of transfomer (kVA)

  f = Supply frequency (Hz)

  ϕ_m = Maximum flux (Wb)

  B_m = Maximum flux density (Wb/m^2)

  δ = Current density (A/mm^2)

  ρ = Resistivity of conductor material (Ω-m)

  A_i = Net cross section area of core (m^2)

  A_{gi} = Gross cross section area of core (m^2)

  A_c = Total copper area in window (m^2)

  A_w = Total area of window (m^2)

  K_w = Window space factor

  T_{HV} = Number of high voltage winding turns

  T_{LV} = Number of low voltage winding turns

  I_{HV} = Phase current in high voltage winding (A)

  I_{LV} = Phase current in low voltage winding (A)

  a_{HV} = Cross section area of high voltage winding conductor (mm^2)

  a_{LV} = Cross section area of low voltage winding conductor (mm^2)

  V_{HV} = Phase voltage of high voltage winding (V)

  V_{LV} = Phase voltage of low voltage winding (V)

  E_{HV} = Phase induced emf in high voltage winding (V)

  E_{LV} = Phase induced emf in low voltage winding (V)

  E_t = Voltage per turn (V)

$$A_c = 2\left[\left(T_{HV} \times a_{HV}\right) + \left(T_{LV} \times a_{LV}\right)\right]$$

$$= 2\left[\left(T_{HV} \times \left(\frac{I_{HV}}{\delta}\right)\right) + \left(T_{LV} \times \left(\frac{I_{LV}}{\delta}\right)\right)\right]$$

$$= \frac{2}{\delta}\left[\left(T_{HV} \times I_{HV}\right) + \left(T_{LV} \times I_{LV}\right)\right]$$

$$= \frac{2}{\delta}\left[\left(\text{mmf of HV winding}\right) + \left(\text{mmf of LV winding}\right)\right]$$

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

$$A_c = \frac{4}{\delta}\left[AT\right]$$

Also, window space factor can be defined as

$$K_w = \frac{\text{Total copper area in window}}{\text{Total area of window}}$$

$$K_w = \frac{A_c}{A_w}$$

$$K_w = \frac{\frac{4}{\delta}\left[AT\right]}{A_w}$$

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

Rating of 3-phase transformer in kVA

$$Q = 3 \times V_{HV} \times I_{HV} \times 10^{-3}$$

$$\cong 3 \times E_{HV} \times I_{HV} \times 10^{-3}$$

$$= 3 \times \left(4.44 \times f \times \phi_m \times T_{HV}\right) \times I_{HV} \times 10^{-3}$$

$$= 3 \times \left(4.44 \times f \times \phi_m\right) \times \left(I_{HV} \times T_{HV}\right) \times 10^{-3}$$

$$= 3 \times \left(4.44 \times f \times \phi_m\right) \times \left(\frac{K_w A_w \delta}{4}\right) \times 10^{-3} \qquad \left(\because AT = \frac{K_w A_w \delta}{4}\right)$$

$$= 3 \times \left(1.11 \times f \times \left(B_m \times A_i\right)\right) \times \left(K_w A_w \delta\right) \times 10^{-3}$$

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

- This output equitation is applicable to both core type and shell type transformer. It helps to optimize design for minimum loss, cost, weight and size.

2.4. Derive equation $E_t = K\sqrt{Q}$. Also explain factors affecting the value of K

- Considering output kVA rating of one phase only.

$$Q = V_{HV} \times I_{HV} \times 10^{-3}$$

$$\cong E_{HV} \times I_{HV} \times 10^{-3}$$

$$= \left(4.44 \times f \times \phi_m \times T_{HV}\right) \times I_{HV} \times 10^{-3}$$

$$= \left(4.44 \times f \times \phi_m\right) \times \left(I_{HV} \times T_{HV}\right) \times 10^{-3}$$

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

$$= \left(4.44 \times f \times \phi_m\right) \times \left(\frac{\phi_m}{r}\right) \times 10^{-3} \qquad \left(\because \frac{\phi_m}{AT} = r, \text{where r is constant}\right)$$

$$= 4.44 \times \left(\phi_m\right)^2 \times \left(\frac{f}{r}\right) \times 10^{-3}$$

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

Voltage per turn,

$$E_t = \frac{E_{HV}}{T_{HV}}$$

$$= \frac{4.44 \times f \times \phi_m \times T_{HV}}{T_{HV}}$$

$$= 4.44 \times f \times \left(\sqrt{\frac{r \times 10^3}{4.44 \times f}}\right)\left(\sqrt{Q}\right)$$

$$= \sqrt{4.44 \times f \times r \times 10^3}\left(\sqrt{Q}\right)$$

$$E_t = K\sqrt{Q}$$

$$\text{Where}, K = \sqrt{4.44 \times f \times r \times 10^3}$$

- Value of voltage per turn depends on selection of factor K, consequentially this factor basically depends on ratio of core cross section area to copper area in window.
- Shell type transformer needs more iron material than copper material compared to core type transformer i.e. value of K will be higher for shell type transformer.
- 1-phase core type transformer needs more iron material than copper material compared to 3-phase core type transformer on per phase basis i.e. value of K will be higher for 1-phase core type transformer.

- Distribution transformer is designed for less iron loss compared to power transformer i.e. less iron material, hence value of K will be low for distribution transformer.
- The usual value of K for different types of transformer is,

  1-phase shell type transformer: 1.00 to 1.20

  1-phase core type transformer: 0.75 to 0.85

  3-phase shell type transformer: 1.30

  3-phase core type transformer (Distribution): 0.45

  3-phase core type transformer (Power): 0.60 to 0.70

2.5. Choice of flux density for transformer design

- Value of flux density in the transformer determines the core area and yoke area, hence computation of flux density is very important and crucial part in design.
- Normally flux density is chosen near knee point of the magnetization curve with some margin to overcome over fluxing, voltage variation and frequency variation.
- Magnetic material used for core and yoke of transformer are hot rolled silicon steel and cold rolled grain oriented silicon steel.
- Choice of flux density may affect the performance parameter such as no load current, behavior under short circuit, iron loss, efficiency and temperature rise.
- Higher value of flux density results in reduced core area and hence there is a saving in iron. With the reduction in core area, the length of mean turn of winding gets reduced which further saves conductor material. Lesser iron and copper material brings down overall cost, weight and size of transformer.
- But higher value of flux density increases the iron loss which results in low efficiency. Increased iron loss causes high temperature rise in core.
- Flux density to be chosen depends on the service condition of the transformer. For distribution transformer high all day efficiency is main design aspect and hence low value of flux density is chosen which keeps down iron loss.
- The usual value of maximum flux density for

  Hot rolled silicon steel core material are:

  Power transformer: 1.25 to 1.45 Wb/m^2

  Distribution transformer: 1.10 to 1.35 Wb/m^2

  Cold rolled grain oriented silicon steel core material are:

  Transformer up to 132 kV: 1.55 Wb/m^2

  Transformer above 275 kV: 1.60 Wb/m^2

  Transformer above 400 kV: 1.70 - 1.75 Wb/m^2

2.6. Choice of current density for transformer design

- The conductor in low voltage and high voltage winding is determined after choosing suitable value of current density.
- Temperature rise may be high if higher value of current density is selected.

- Current density selection is significant for I^2R loss, hence the load at which maximum efficiency occurs depends on it.
- The level of I^2R loss required is different in distribution and power transformer. Thus the value of current density is different for different type of transformer.

  Self-cooled transformer: 1.1 – 2.3 A/mm²

  Forced air cooled transformer: 2.2 – 3.2 A/mm²

  Forced oil cooled transformer: 5.4 – 6.2 A/mm²

2.7. Selection of window dimension

- Leakage reactance of transformer depends on distance between adjacent limbs.
- When distance between limbs are small, winding is accommodated by increasing the height i.e. winding is long and thin. This arrangement leads to low value of leakage reactance.
- When distance between limbs are large, winding is accommodated by increasing the width i.e. winding is short and wide. This arrangement leads to high value of leakage reactance.
- The area of window depends upon the total conductor area and window space factor. Total area of window is defined as

$$A_w = \frac{\text{Total copper area in window}}{\text{Window space factor}} = \frac{2\left[\left(T_{HV} \times a_{HV}\right) + \left(T_{LV} \times a_{LV}\right)\right]}{K_w}$$

Also

$$A_w = H_w \times W_w$$

- The ratio of height to width H_w/W_w is selected between 2 to 4 to achieve suitable arrangement of winding height and width.

2.8. Choice of window space factor for transformer design

- Window space in transformer is fully occupied by conductor material and insulating material. Hence window space factor is defined as the ratio of total copper area in window to total area of window.

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

- Value of K_w, depends on transformer power and voltage rating. Following empirical formula is used for estimating the value of window space factor.

$$K_w = \frac{8}{30 + kV} \text{ for transformer rating above 20 } kVA$$

$$K_w = \frac{10}{30 + kV} \text{for transformer rating 50 - 200 } kVA$$

$$K_w = \frac{12}{30 + kV} \text{for transformer rating of about 1000 } kVA$$

(a) Variation in Window space factor (K_w) with kVA rating

- Transformers with the same voltage rating but different kVA rating (i) 100 kVA (ii) 1000 kVA, needs same insulating material and large copper material for 1000 kVA compared to 100 kVA. Hence, window space factor value increases as power rating of transformer increases.

(b) Variation in Window space factor (K_w) with kV rating

- Transformers with same power rating but different kV rating (i) 11 kV (ii) 110 kV, needs less copper material and more insulating material in 110 kV compared to 11 kV. Hence, window space factor value decreases as voltage level of winding increases.

2.9. Selection of core cross section for transformer design

- In a transformer, there are low voltage and high voltage windings. The performance of a transformer mainly depends upon the flux linkages between these windings and low reluctance magnetic path is required to link flux between these windings. This low reluctance magnetic path is known as core of transformer.
- Core section of transformer can be square or stepped. These shapes of core can be advantages for circular coils. Distribution and power transformer uses circular coils because mechanical stresses produced at the time of short circuit are radial and hence there is no tendency for the coil to change its shape.
- In small transformer square cores are used. As the size of transformer increase, size of core increase and hence lot of useful space is wasted. Further with the increase in circumscribing circle diameter, length of mean turn of winding increases, which will will rise I^2R loss and conductor cost.
- In large transformer, cruciform cores are used. For same core area, space utilization is batter in cruciform cores compared to square core. Further reduction in circumscribing circle diameter, length of mean turn of winding reduces giving low I^2R loss and conductor cost.

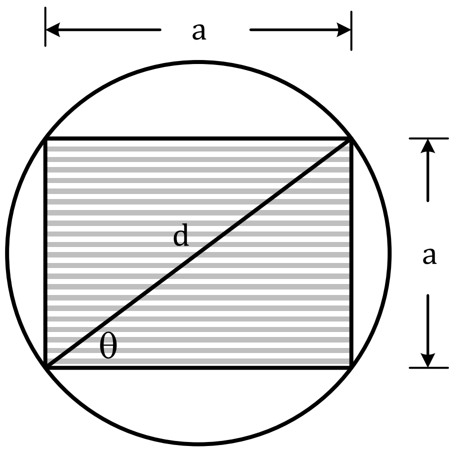

Figure 2. 3 Square core

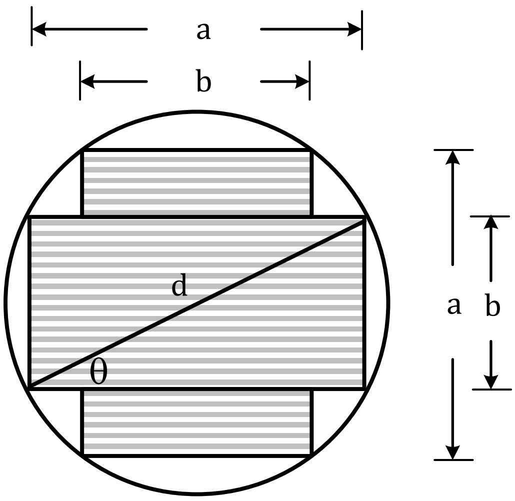

Figure 2. 4 Cruciform core

(a) Square core

$$\text{Circumscribing circle diameter} = \sqrt{\left(a^2 + a^2\right)}$$
$$d = 1.414a$$
$$\therefore \ a = 0.707d$$

$$\text{Gross area of core} = a \times a$$
$$A_{gi} = \left(0.707d\right) \times \left(0.707d\right)$$
$$= 0.5d^2$$

$$\text{Staking factor, } K_s = \frac{\text{Net area of core}}{\text{Gross area of core}} = \frac{A_i}{A_{gi}}$$

$$\therefore \text{Net area of core} = K_s \times A_{gi}$$
$$A_i = \left(0.9\right) \times \left(0.5d^2\right)$$
$$= 0.45d^2$$

$$\frac{\text{Net area of core}}{\text{Circumscribing circle area}} = \frac{0.45d^2}{\frac{\Pi}{4}d^2} = 0.58$$

$$\frac{\text{Gross area of core}}{\text{Circumscribing circle area}} = \frac{0.5d^2}{\frac{\Pi}{4}d^2} = 0.64$$

(b) Cruciform Core

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

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

$$\text{To have maximum area, } \frac{dA_{gi}}{d\theta} = 0$$

$$\frac{d(d^2\left(\sin 2\theta - \sin^2\theta\right)}{d\theta} = 0$$

$$2\cos 2\theta - 2\sin\theta\cos\theta = 0$$
$$2\cos 2\theta - \sin 2\theta = 0$$
$$2\cos 2\theta = \sin 2\theta$$
$$\tan 2\theta = 2$$
$$\theta = 31.71$$

$$\text{Gross area of core} = d^2\left(\sin\left(2\times 31.71\right) - \sin^2\left(31.71\right)\right)$$
$$A_{gi} = 0.618d^2$$
$$\text{Net area of core} = K_s \times A_{gi}$$
$$A_i = \left(0.9\right)\times\left(0.618d^2\right)$$
$$= 0.56d^2$$
$$\frac{\text{Net area of core}}{\text{Circumscribing circle area}} = \frac{0.56d^2}{\frac{\Pi}{4}d^2} = 0.71$$
$$\frac{\text{Gross area of core}}{\text{Circumscribing circle area}} = \frac{0.618d^2}{\frac{\Pi}{4}d^2} = 0.79$$

- Most economical dimension of stepped cores are given as fraction of diameter of circumscribing circle. In actual practice laminations are available in standard size to avoid wide variety and wastage of material so, transformer cores are made with standard step size.

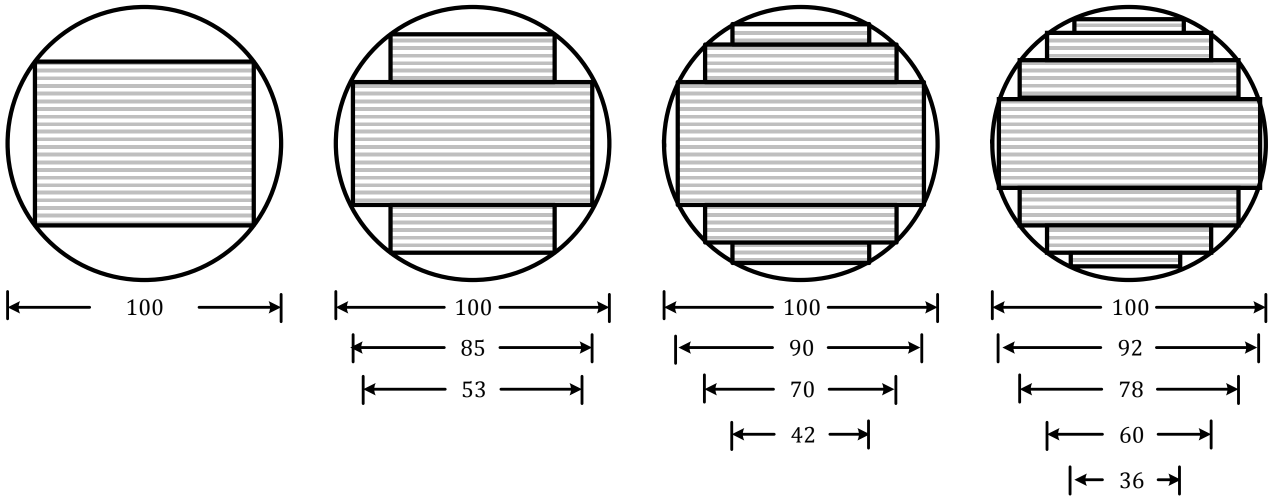

Figure 2. 5 Most economical dimension of stepped cores

- By increasing number of steps, the area of circumscribing circle is more effectively utilized. Most economical dimensions of various step size are tabulated below.

Area % of circumscribing circle	Square	Cruciform	Three	Four
Gross area of core	64	79	84	87
Net area of core	58	71	75	78
$A_i = K_c d^2$	0.45	0.56	0.6	0.62

2.10. Selection of yoke cross section for transformer design

- A yoke is a fixed magnetic part of transformer core which completes the flux path.
- It is not surrounded by a winding.

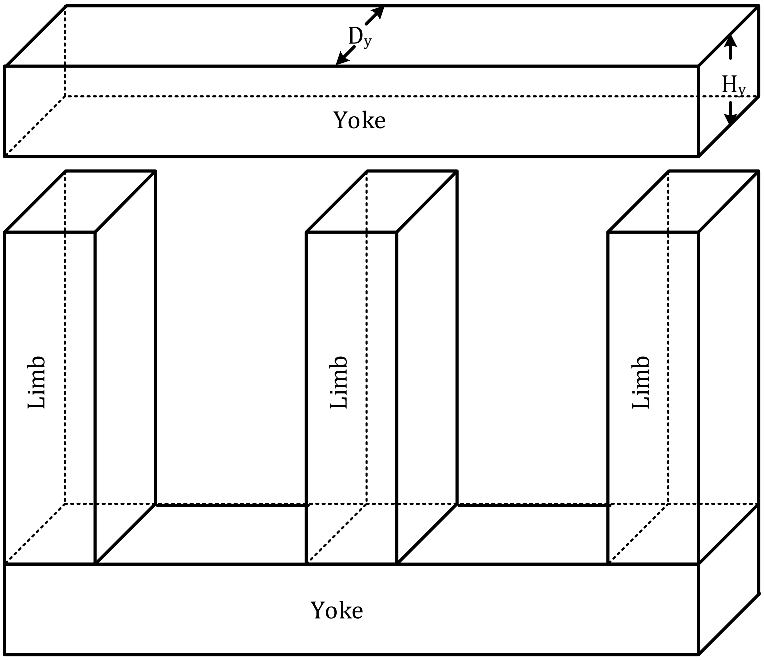

Figure 2. 6 Yoke dimensions

- Yoke with rectangular cross section is used for small transformer, however for medium and large transformer two or three stepped yoke is used.
- Number of steps in yoke is much lesser than steps in core hence, unequal distribution of magnetic flux along yoke cross section will give rise to iron loss and no load current in yoke.
- To overcome above said difficulty, cross section area of yoke is taken 10 to 20 % more than cross section area of core.

Net area of yoke,

$$A_y = (1.10 \text{ } to \text{ } 1.20) \times A_i$$

Width of yoke,

$$D_y = \text{largest stamping size} = a$$

Height of yoke,

$$H_y = \frac{A_y}{D_y}$$

Flux density in yoke,

$$B_y = \frac{\text{Flux in yoke}}{\text{Net area of yoke}} = \frac{\phi_y}{A_y} = \frac{\phi_m}{A_y}$$

2.11. Overall all dimensions of 3-Ø transformer

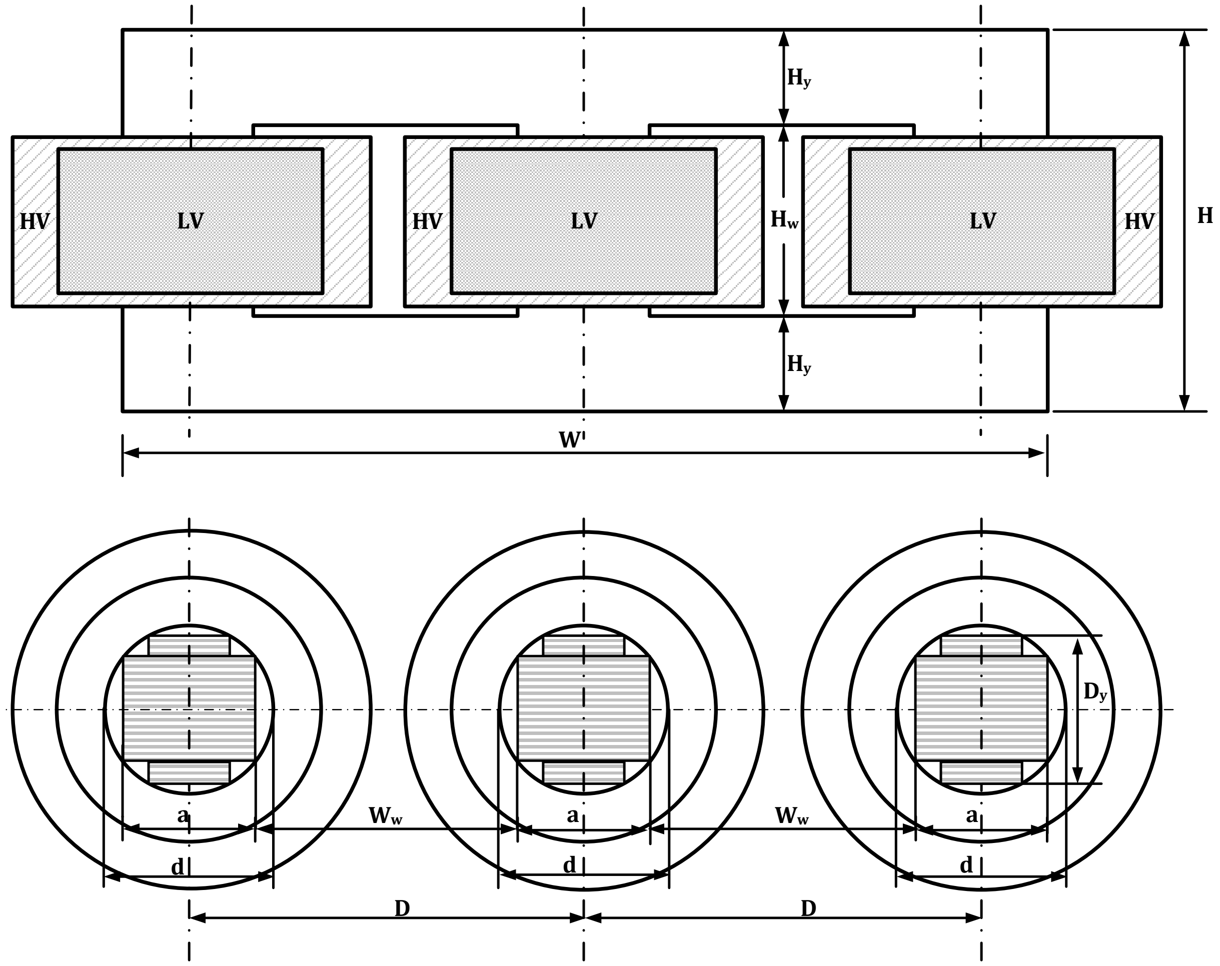

Figure 2. 7 Overall dimensions

D = Distance between core center (m)

d = Circumscribing circle diameter (m)

a = Width of largest stamping (m)

W_w = Width of window (m)

H_w = Heigth of window (m)

D_y = Width of yoke (m)

H_y = Heigth of yoke (m)

W = Width of frame (m)

H = Heigth of frame (m)

Hence,

$$D = W_w + \frac{a}{2} + \frac{a}{2} = W_w + a$$

$$W = 2D + \frac{a}{2} + \frac{a}{2} = 2D + a$$

$$H = H_w + H_y + H_y = H_w + 2H_y$$

2.12. Selection of winding used for transformer design

- In transformer, winding type is chosen to match desired electrical characteristics and adequate mechanical strength. Some times more than one type of winding may be suitable. In this case, the winding which is simple in construction will be used. Windings are usually of the following types;

(a) Cylindrical winding

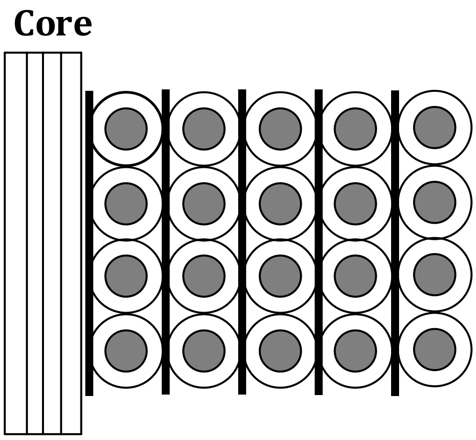

Figure 2. 8 Cylindrical winding with circular conductor

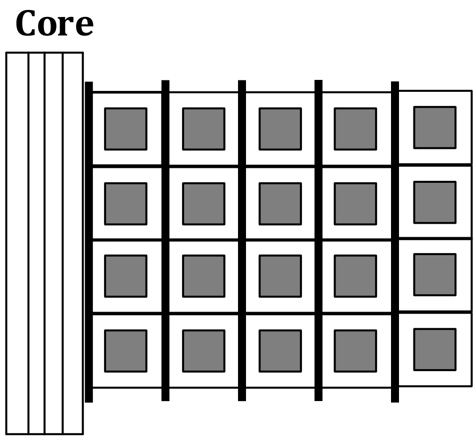

Figure 2. 9 Cylindrical winding with rectangular conductor

- Cylindrical windings are layer type and uses either circular or rectangular conductor. The layered winding may have conductors wound in one, two or more layer and therefore, accordingly called one, two or multi-layer winding.
- It is used for large current with number of parallel conductors located side by side in one layer. Parallel conductors have same length and located in almost same magnetic field, hence they are not transposed.
- Two layers of cylindrical windings are separated by an oil duct in order to improve oil cooling of inner layer.
- Cylindrical windings with circular conductor are mainly used for high voltage ratings 6.6 kV, 11 kV, 33 kV for power rating up to 600 kVA.
- Cylindrical windings with rectangular conductor are mainly used for low voltage ratings 0.415 kV, 6.6 kV for power rating up to 750 kVA.

(b) Cross over winding

- Cross over winding are used for high voltage winding of small transformer.
- When cylindrical windings are used for high voltage winding of small transformer, voltage between adjacent layers becomes too high and hence it becomes difficult to select thickness of interlayer insulation.
- Thus it necessary to reduce interlayer insulation. It is achieved by dividing winding in number of coils separated by a distance of 0.5 to 1mm with the help of insulating washer or oil duct.
- The voltage between adjacent coils should not exceed 800 to 1000 volt, hence

$$\text{Number of coil} > \frac{\text{Voltage rating of winding}}{800 \text{ to } 1000}$$

- In cross over winding, the conductors are paper covered circular or rectangular. Each coils are wound over formers and it consists of number of layers.

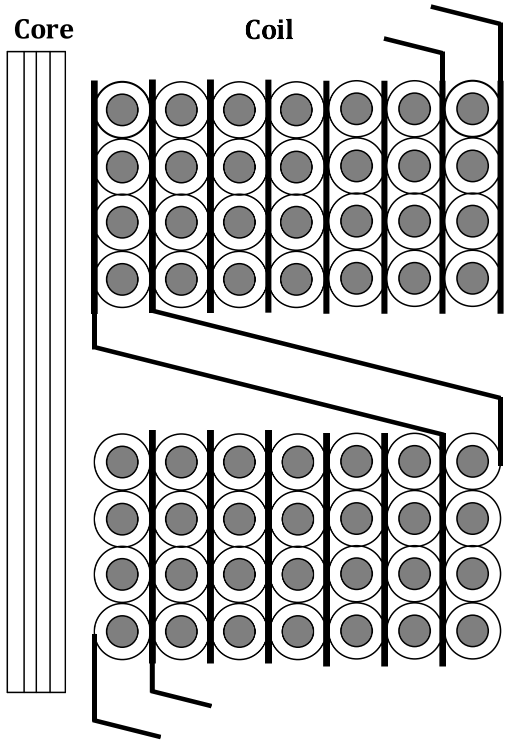

Figure 2. 10 Cross-over winding with circular conductor

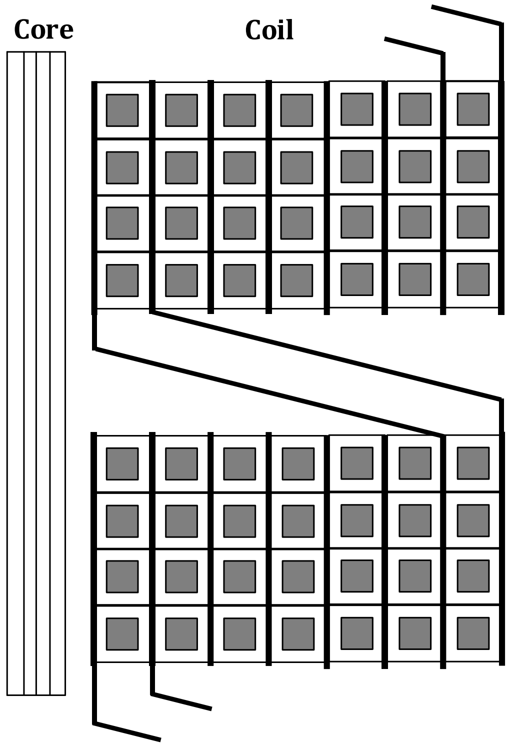

Figure 2. 11 Cross-over winding with rectangular conductor

- Complete winding consist of coils connected in series. Two end of coils are brought out for series connection. Outside end of one coil is connected to inside end of adjacent coil.
- Cross over winding is used in the same range of ratings as cylindrical windings. Cross over winding have higher strength than cylindrical winding under normal operating condition.
- This winding have lower impulse strength than cylindrical winding.

(c) Helical winding

- Helical windings are used for low voltage winding of power transformer where number of winding turns are small but current is high.
- These type of windings are designed with rectangular conductor cross section connected in parallel and placed with side by side in radial direction.
- In order to secure mechanical strength, rectangular conductor with cross section area not less than 100 mm^2 is used for winding.
- Usually (i) single helical (ii) double helical (iii) multi-layer helical windings are used for voltage ratings of 0.230 to 15 kV for power rating up to 10,000 kVA.
- In single helical winding conductors are placed side by side to form one turn. Each turn is separated by spacers along the axial length.
- In double helical winding conductors placed side by side forming one turn are divided into two parallel path and they are shifted to axial direction to form two layer.

- Double helical winding is commonly used because less number of parallel conductor in radial direction and large number of parallel conductor in axial direction allows more axial magnetic field to link with winding.
- Magnetic field is uniform in axial direction while non-uniform in radial direction, therefore greater magnetic regularity is achieved in double helical winding. It will result in less I^2R loss and leakage reactance.

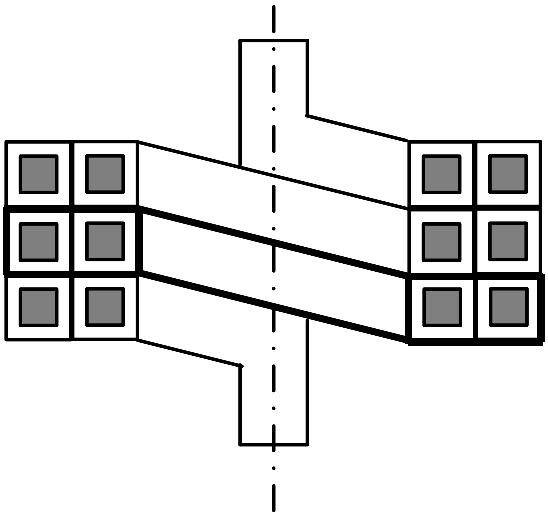

Figure 2. 12 Single helical winding

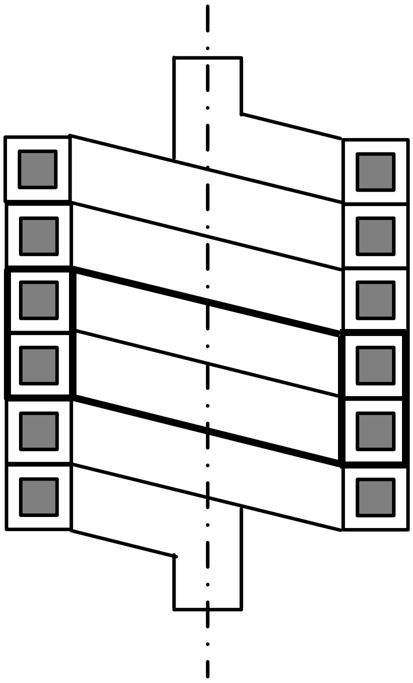

Figure 2. 13 Double helical winding

- Multi-layer helical winding is generally used for voltage rating above 110 kV. It consists of several cylindrical layers wound and connected in series. Outer layer is made shorter than inner layer to distribute capacitance uniformly.
- Multi-layer helical winding is prefered to improve surge behavior of transformer but improvement in surge behavior requires large capacitance. It is achieved by reducing radial depth of winding. When radial depth of winding reduces, mechanical strength of winding becomes inferior. Therefore use of multi-layer helical winding is restricted.
- Helical windings are used for current rage 300-2400 A. Double helical winding is used for the same range of voltage used in single helical. However current rating for double helical winding is twice of single helical winding.

(d) Disc winding

- Disc windings are primarily used in high capacitor voltage transformer for current rage 12-600 A.
- This winding consists of single layer disc coil wound with rectangular conductor connected in series and parallel. Coils are wound spirally from center outwards in the radial direction.

- Each coil rests on pressboard spacers forming horizontal duct. Width of radial oil duct depends upon voltage between adjacent coils, specific thermal loading and nature of transformer cooling.

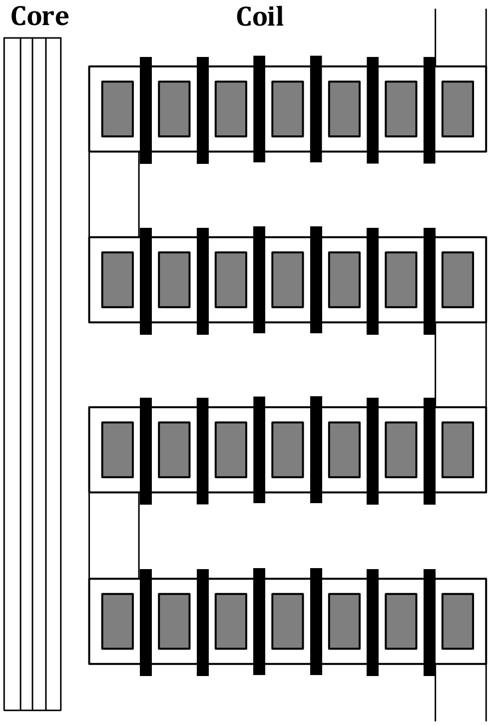

Figure 2. 14 Disc winding

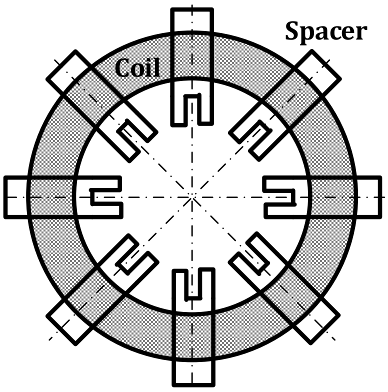

Figure 2. 15 Arrangement of spacer in disc winding

- Number of coils should be chosen such that necessary winding height utilizes standard size of conductor. Windings are designed for voltage 33 to 110 kV normally uses 60 to 80 coils.
- Number of coils in continuous disc winding with taping at middle should be multiple of four.
- Distinguished feature of continuous disc winding is transposition of coils.

Low voltage winding design	**High voltage winding design**
Number of turn $T_{LV} = \frac{V_{LV}}{E_t}$ Current $I_{LV} = \frac{kVA \times 10^3}{3V_{LV}}$ Conductor cross section area $a_{LV} = \frac{I_{LV}}{\delta}$	Number of turn $T_{HV} = \frac{V_{HV}}{E_t}$ Current $I_{HV} = \frac{kVA \times 10^3}{3V_{HV}}$ Conductor cross section area $a_{HV} = \frac{I_{HV}}{\delta}$

- Outer position, low current capacity and more number of available turn on high voltage side benefits switching. Hence, tapings are provided on high voltage side.

2.13. Winding resistance of 3-Ø core type transformer

ρ = resistivity of conductor material (Ω-m)

T_{HV} = Number of high voltage winding turns

T_{LV} = Number of low voltage winding turns

I_{HV} = Phase current in high voltage winding (A)

I_{LV} = Phase current in low voltage winding (A)

a_{HV} = Cross section area of high voltage winding conductor (mm^2)

a_{LV} = Cross section area of low voltage winding conductor (mm^2)

r_{HV} = Resistance of high voltage winding (Ω)

r_{LV} = Resistance of low voltage winding (Ω)

Lmt_{HV} = Length of mean turn of high voltage winding (m)

Lmt_{LV} = Length of mean turn of low voltage winding (m)

$Lmt_{HV} = Lmt_{LV} = L_o = Lmt$

Resistance of winding

$$r_{HV} = \rho \frac{(Lmt_{HV})(T_{HV})}{a_{HV}}$$

$$r_{LV} = \rho \frac{(Lmt_{LV})(T_{LV})}{a_{LV}}$$

Total resistance referred to high voltage winding

$$R_{HV} = r_{HV} + \left(\frac{T_{HV}}{T_{LV}}\right)^2 r_{LV}$$

Per unit resistance

$$\varepsilon_r = \frac{I_{HV} R_{HV}}{V_{HV}}$$

2.14. Winding leakage reactance of 3-Ø core type transformer clearly stating the assumptions used

- **Assumptions**
  - High voltage and low voltage winding have equal axial length.
  - Flux path is parallel to the windings along the axial length.
  - Mmf required to iron path is negligible.
  - High voltage winding mmf and low voltage winding mmf is equal, hence magnetizing mmf and magnetizing current is zero.
  - Half of the leakage flux in the duct links with each winding.
  - Length of mean turn of each winding is equal.
  - Reluctance of flux path through yoke negligible.
  - Windings are uniformly distributed, hence winding mmf varies uniformly from zero to AT from one end to another end.

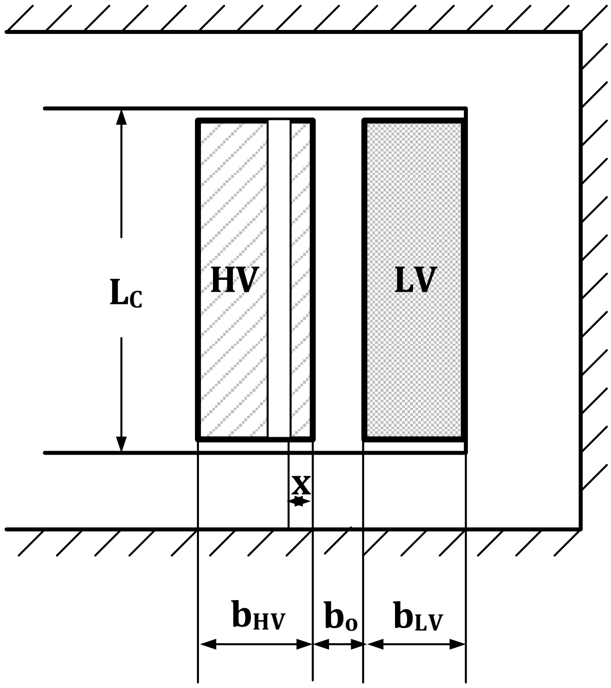

Figure 2. 16 Leakage flux distribution in core type transformer

(a) Conductor section

- Consider a small infinite strip of width dx at a distance x from the edge of high voltage winding along its width.

$$\text{Mmf across strip } = \left(\frac{x}{b_{HV}}\right)\left(I_{HV}T_{HV}\right)$$

$$\text{Permeance of strip } = \frac{1}{\text{Reluctance}} = \frac{1}{\frac{L_C}{\mu_0 A}} = \frac{\mu_0 A}{L_C} = \frac{\mu_0\left(Lmt_{HV}dx\right)}{L_C} = \mu_0\left(\frac{Lmt_{HV}}{L_C}\right)dx$$

$$\text{Flux in strip} = \left(\text{Mmf}\right)\left(\text{Permeance }\right) = \left[\left(\frac{x}{b_{HV}}\right)\left(I_{HV}T_{HV}\right)\right]\left[\mu_0\left(\frac{Lmt_{HV}}{L_C}\right)dx\right]$$

$$\text{Flux linkages of the strip} = \left[\left(\frac{x}{b_{HV}}\right)\left(T_{HV}\right)\right]\left[\mu_0\left(\frac{Lmt_{HV}}{L_C}\right)\left(I_{HV}T_{HV}\right)\left(\frac{x}{b_{HV}}\right)dx\right]$$

$$d\psi_1 = \mu_0\left(\frac{Lmt_{HV}}{L_C}\right)I_{HV}\left(T_{HV}\right)^2\left(\frac{x}{b_{HV}}\right)^2 dx$$

$$\text{Flux linkages of high voltage winding } = \int_0^{b_{HV}} d\psi_1$$

$$\psi_1 = \mu_0\left(\frac{Lmt_{HV}}{L_C}\right)I_{HV}\left(T_{HV}\right)^2\int_0^{b_{HV}}\left(\frac{x}{b_{HV}}\right)^2 dx$$

$$\psi_1 = \mu_0\left(\frac{Lmt_{HV}}{L_C}\right)I_{HV}\left(T_{HV}\right)^2\left(\frac{b_{HV}}{3}\right)$$

(b) Duct section

Mmf across duct $= \left(I_{HV}T_{HV}\right)$

Permeance of duct $= \dfrac{1}{\text{Reluctance}} = \dfrac{1}{\dfrac{L_C}{\mu_0 A}} = \dfrac{\mu_0 A}{L_C} = \dfrac{\mu_0\left(L_o b_o\right)}{L_C} = \mu_0\left(\dfrac{L_o}{L_C}\right)b_o$

Flux in duct $= \left(\text{Mmf}\right)\left(\text{Permeance}\right) = \left[\left(I_{HV}T_{HV}\right)\right]\left[\mu_0\left(\dfrac{L_o}{L_C}\right)b_o\right]$

Flux linkages of high voltage winding due to duct flux

$$\psi_0 = \left(\text{Half of flux in duct}\right)\left(T_{HV}\right)$$

$$= \left[\mu_0\left(\frac{L_o}{L_C}\right)I_{HV}\left(T_{HV}\right)^2\left(\frac{b_o}{2}\right)\right]\left(T_{HV}\right)$$

$$= \mu_0\left(\frac{L_o}{L_C}\right)I_{HV}\left(T_{HV}\right)^2\left(\frac{b_o}{2}\right)$$

Total flux linkages of high voltage winding

$$\psi_{HV} = \psi_1 + \psi_0$$

$$= \mu_0\left(\frac{Lmt_{HV}}{L_C}\right)I_{HV}\left(T_{HV}\right)^2\left(\frac{b_{HV}}{3}\right) + \mu_0\left(\frac{L_o}{L_C}\right)I_{HV}\left(T_{HV}\right)^2\left(\frac{b_o}{2}\right)$$

$$= \mu_0\frac{I_{HV}\left(T_{HV}\right)^2}{L_C}\left(Lmt_{HV}\left(\frac{b_{HV}}{3}\right) + L_o\left(\frac{b_o}{2}\right)\right)$$

If, it is assumed that $Lmt_{HV} = Lmt_{LV} = L_o = Lmt$

$$\psi_{HV} = \mu_0 I_{HV}\left(T_{HV}\right)^2\frac{Lmt}{L_C}\left(\frac{b_{HV}}{3} + \frac{b_o}{2}\right)$$

Leakage inductance of high voltage winding

$$L_{HV} = \mu_0\left(T_{HV}\right)^2\frac{Lmt}{L_C}\left(\frac{b_{HV}}{3} + \frac{b_o}{2}\right)$$

Leakage reactance of high voltage winding

$$x_{HV} = 2\pi f\mu_0\left(T_{HV}\right)^2\frac{Lmt}{L_C}\left(\frac{b_{HV}}{3} + \frac{b_o}{2}\right)$$

Similarly,leakage reactance of low voltage winding

$$x_{LV} = 2\pi f\mu_0\left(T_{LV}\right)^2\frac{Lmt}{L_C}\left(\frac{b_{LV}}{3} + \frac{b_o}{2}\right)$$

Total leakage reactance referred to high voltage winding

$$X_{HV} = x_{HV} + \left(\frac{T_{HV}}{T_{LV}}\right)^2 x_{LV}$$

2.15. Losses in 3-Ø transformer and condition for maximum efficiency

- Losses in transformer are of two types (i) Copper loss (P_c) (ii) Iron loss (P_i).

  Total Copper loss

  $$P_c = 3\left(I_{HV}\right)^2 R_{HV}$$

  Total iron loss

  $$P_i = 3\left(\text{Iron loss in limb}\right) + 2\left(\text{Iron loss in yoke}\right)$$
  $$= 3P_{i\,Limb} + 2P_{i\,Yoke}$$
  $$P_{Limb} = \text{Height of window} \times \text{Net iron area} \times \text{Density of lamination} \times \text{Sp. iron loss}$$
  $$= H_w \times A_i \times \text{Density of lamination} \times \text{Sp. iron loss}$$
  $$P_{Yoke} = \text{Width of frame} \times \text{Net area of yoke} \times \text{Density of lamination} \times \text{Sp. iron loss}$$
  $$= W \times A_y \times \text{Density of lamination} \times \text{Sp. iron loss}$$

  Total loss

  $$P = P_C + P_i + \text{Stray load loss}$$

- Transformer may be designed for maximum efficiency i.e. minimum losses.

  $$\text{Total loss at full load} = P_C + P_i$$
  $$\text{Total loss at any fraction (x) of full load} = (x)^2 P_C + P_i$$
  $$\text{Efficiency at any fraction (x) of full load, } \eta_x = \frac{(x)\left(kVA \times 10^3\right)(\cos\phi)}{(x)\left(kVA \times 10^3\right)(\cos\phi) + (x)^2 P_C + P_i}$$
  $$= \frac{(x)\left(Q \times 10^3\right)(\cos\phi)}{(x)\left(Q \times 10^3\right)(\cos\phi) + (x)^2 P_C + P_i}$$
  $$\text{Efficiency is maximum when } \frac{d\eta_x}{dx} = 0$$
  $$\frac{\left[(x)\left(Q \times 10^3\right)(\cos\phi) + (x)^2 P_C + P_i\right]\left[\left(Q \times 10^3\right)(\cos\phi)\right] - \left[(x)\left(Q \times 10^3\right)(\cos\phi)\right]\left[\left(Q \times 10^3\right)(\cos\phi) + (2x)P_C\right]}{\left[(x)\left(Q \times 10^3\right)(\cos\phi) + (x)^2 P_C + P_i\right]^2} = 0$$
  $$\left[(x)\left(Q \times 10^3\right)(\cos\phi) + (x)^2 P_C + P_i\right]\left[\left(Q \times 10^3\right)(\cos\phi)\right] - \left[(x)\left(Q \times 10^3\right)(\cos\phi)\right]\left[\left(Q \times 10^3\right)(\cos\phi) + (2x)P_C\right] = 0$$
  $$\left[(x)\left(Q \times 10^3\right)(\cos\phi) + (x)^2 P_C + P_i\right] - (x)\left[\left(Q \times 10^3\right)(\cos\phi) + (2x)P_C\right] = 0$$
  $$(x)\left(Q \times 10^3\right)(\cos\phi) + (x)^2 P_C + P_i - (x)\left(Q \times 10^3\right)(\cos\phi) - 2(x)^2 P_C = 0$$
  $$(x)^2 P_C + P_i - 2(x)^2 P_C = 0$$
  $$P_i - (x)^2 P_C = 0$$
  $$P_i = (x)^2 P_C$$

  Iron loss = Copper loss

  Constant loss = Variable loss

2.16. No load current of 3-Ø transformer

- When transformer operates at no load, current at secondary winding is zero but primary winding draws small current known as no load current.
- No load current of a transformer consists of two component (i) Magnetizing component (I_m) (ii) Loss component (I_l).

Total magnetizing mmf per phase

$$AT_o = \frac{3(\text{Mmf of limb})+2(\text{Mmf of yoke})+\text{Mmf of joints}}{3}$$

$$AT_o = \frac{3at_c l_c + 2at_y l_y + \text{Mmf of joints}}{3}$$

Total iron per phase

$$P_i = \frac{\text{Total iron loss}}{3}$$

Magnetizing component of current per phase

$$I_m = \frac{AT_o}{\sqrt{2}T_{HV}}$$

Loss component of current per phase

$$I_l = \frac{P_i}{V_{HV}}$$

No load current per phase

$$I_o = \sqrt{(I_m)^2 + (I_l)^2}$$

- Magnetizing component (I_m) produces the magnetic flux in the core, while loss component (I_l) produces real power to feed total iron loss.
- Magnitude of magnetizing component (I_m) depends upon quality of magnetic material used for core and yoke, flux density selected and type of joints.
- Magnitude of loss component (I_l) depends upon total iron loss.
- Loss component (I_l) is very small compared to magnetizing component (I_m). No load current is in order of percentage of rated current of transformer.

  Small transformer: 3.0 – 5.0 % of rated current

  Medium transformer: 1.0 – 3.0 % of rated current

  Large transformer: 0.5 – 2.0 % of rated current

2.17. Design optimization condition for the minimum cost

- Design optimization is a technique in which certain design variables are needed to be determined to achieve the best measurable performance under given constraints.
- Transformer can be designed to make one of the quantity (i) volume (ii) weight (iii) cost (iv) losses as minimum. These requirements are contradictory and not possible to satisfy all for one design.

Output equation of transformer

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

As product $\left(3.33 f B_m \delta \times 10^{-3}\right)$ is constant for given rating, let assume $A_i A_c = M^2$

$$Also,\ r = \frac{\phi_m}{AT} = \frac{B_m A_i}{\frac{K_w A_w \delta}{4}} = \frac{4 B_m A_i}{A_c \delta}$$

$$\frac{A_i}{A_c} = \frac{r\delta}{4B_m} = \beta$$

$$A_i = M\sqrt{\beta}\ and\ A_c = \frac{M}{\sqrt{\beta}}$$

$If,$

C_t = Total cost of transformer active material (Rs)

C_i = Total cost of iron (Rs)

C_c = Total cost of copper

c_i = Specific cost of iron (Rs/Kg)

c_c = Specific cost of copper (Rs/Kg)

G_i = Weight of iron (Kg)

G_c = Weight of copper (Kg)

g_i = Density of iron = $7.8 \times 10^3 (\mathrm{Kg/m^3})$

g_c = Density of copper = $8.9 \times 10^3 (\mathrm{Kg/m^3})$

$$\begin{aligned} C_t &= C_i + C_c \\ &= c_i G_i + c_c G_c \\ &= c_i A_i l_i g_i + c_c A_c L_{mt} g_c \\ &= c_i \left(M\sqrt{\beta}\right) l_i g_i + c_c \left(\frac{M}{\sqrt{\beta}}\right) L_{mt} g_c \end{aligned}$$

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

$$c_i M \left(\frac{1}{2}\beta^{-\frac{1}{2}}\right) l_i g_i + c_c M \left(-\frac{1}{2}\beta^{-\frac{3}{2}}\right) L_{mt} g_c = 0$$

$$c_i M \left(\frac{1}{2}\beta^{-\frac{1}{2}}\right) l_i g_i - c_c M \left(\frac{1}{2}\beta^{-\frac{3}{2}}\right) L_{mt} g_c = 0$$

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

$$c_i l_i g_i = c_c L_{mt} g_c \beta^{-1}$$

$$c_i l_i g_i = c_c L_{mt} g_c \left(\frac{A_c}{A_i}\right)$$

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

$$c_i G_i = c_c G_c$$

Cost of iron= Cost of Copper

2.18. Area of core affected by weight of copper and iron

$$\text{Ratio}\frac{\text{Weight of iron}}{\text{Weigth of copper}}=\frac{G_i}{G_c}=\frac{A_i l_i g_i}{A_c L_{mt} g_c}=\frac{A_i l_i g_i}{K_w A_w L_{mt} g_c}$$

$$\therefore K_w A_w=\left(\frac{G_c}{G_i}\right)\left(\frac{A_i l_i g_i}{L_{mt} g_c}\right)$$

$$=\left(\frac{l_i g_i}{L_{mt} g_c}\right)\left(\frac{G_c A_i}{G_i}\right)$$

$$=K_1\left(\frac{G_c A_i}{G_i}\right)$$

$$\text{Where, } K_1=\left(\frac{l_i g_i}{L_{mt} g_c}\right)$$

Output equation of transformer

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

$$=3.33 f B_m A_i K_1\left(\frac{G_c A_i}{G_i}\right)\delta\times 10^{-3}$$

$$=3.33 f B_m A_i^2 K_1 \frac{G_c}{G_i}\delta\times 10^{-3}$$

$$\therefore A_i^2=\frac{Q}{3.33 f B_m K_1 \frac{G_c}{G_i}\delta\times 10^{-3}}$$

$$A_i=\sqrt{\frac{10^3}{3.33K_1}\frac{Q}{f B_m \delta}\frac{G_i}{G_c}}$$

2.19. Effect of change in linear dimensions on output and losses of transformer

- Consider two transformer of same flux density, current density, frequency, window space factor and type with linear dimension in the ratio of x:1.
- Let, transformer with dimension x is called A and other transformer B.

(a) Effect on output

Output of transformer, $Q\propto f B_m A_i K_w A_w \delta$

Where,

$A_w \propto x^2$ and $A_i \propto x^2$

$\therefore Q\propto A_i A_w \propto x^4$

(b) Effect on losses

Total iron loss, $P_i=\text{loss per unit volume}\times\text{volume}$

$$\therefore P_i\propto x^3$$

Total copper loss, $P_c = 3\left(I_{HV}\right)^2 r_{HV} + 3\left(I_{LV}\right)^2 r_{LV}$

$$= 3\left[\left(\delta a_{HV}\right)^2 \rho \frac{\left(Lmt_{HV}\right)\left(T_{HV}\right)}{a_{HV}} + \left(\delta a_{LV}\right)^2 \rho \frac{\left(Lmt_{LV}\right)\left(T_{LV}\right)}{a_{LV}}\right]$$

$$= 3\delta^2 \rho \left[a_{HV} T_{HV} Lmt_{HV} + a_{LV} T_{LV} Lmt_{LV}\right]$$

$$= 3\delta^2 \rho \left[\text{Total volume of copper}\right]$$

$$\therefore P_c \propto x^3$$

2.20. Effect of change in frequency on losses, voltage and leakage impedance of transformer

(a) Effect on losses

$$Specific\ iron\ loss,\ P_i = Hysteresis\ loss + Eddy\ current\ loss$$

$$= P_h + P_e$$

$$= k_h f B_m{}^2 + k_e f^2 B_m{}^2$$

- If voltage of transformer is constant, the product (fB_m) will be constant.

$$Let,\ product\ \left(fB_m\right) = K$$

Eddy current loss, $P_e = k_e f^2 B_m{}^2$

$$= k_e f^2 \left(\frac{K}{f}\right)^2$$

$$= k_e \left(K\right)^2$$

$$= \text{constant}$$

Hysteresis loss, $P_h = k_h f B_m{}^2$

$$= k_h f \left(\frac{K}{f}\right)^2$$

$$= \frac{k_h K^2}{f}$$

$$= \text{Inversely varies with frequency}$$

- Eddy current loss will remain constant even though frequency is changed and hysteresis loss will increase with the decrease in frequency.

(b) Effect on voltage

- Change in frequency do not affect the voltage of any side of transformer as voltage depends on amount of winding. However it may change the field strength of core and possibly saturation of it.

(c) Effect on leakage impedance

- Change in frequency do not have much effect on leakage impedance.
- Leakage reactance will increase linearly with the increase in frequency and *vice versa*.

- Due to skin effect, effective resistance will increase with the increase in frequency and *vice versa.* This effect is negligible for the small change in frequency.

2.21. Mechanical forces developed in transformer windings

- Transformer windings under normal operating conditions are subjected to mechanical forces such as
    - Force of attraction due to current flowing in same direction
    - Force of repulsion due to current flowing in opposite direction
- The magnitude of force on conductor is proportional to product of current in conductor and intensity of magnetic field due to neighboring conductor. Under normal condition current is small, so forces are moderate and not noticeable.
- At the time of short circuit at full voltage current may reach to 10-25 times full load current hence, mechanical forces will reach to 100-625 times normal forces.
- For circular coil, forces are radial hence there will not be any tendency to change the shape of coil. While on rectangular coil, forces are perpendicular to conductor that will tend to deform coil in circular form. Thus circular coils are preferred in transformer winding.

(a) Radial force

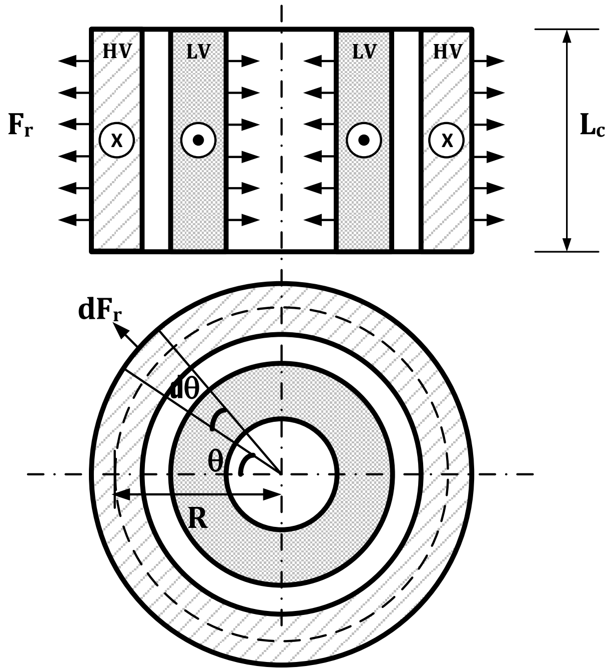

Figure 2. 17 Radial force on winding

- Interaction of axial component of leakage flux with current carrying conductor produces force in radial direction.
- Radial force tries to burst the outer winding and crush inner winding. This is because primary and secondary winding carries current in opposite direction and hence repulsive force pulls outer winding and compress inner winding.

Instantaneous mmf acting across the duct $= iT$

Flux density in duct $= \mu_0 \mu_r H = \mu_0 \dfrac{iT}{L_c}$

Average flux density in duct $= \dfrac{\mu_0 \dfrac{iT}{L_c}}{2} = \mu_0 \dfrac{iT}{2L_c}$

Radial force acting on a strip at mean radius R within an angle dθ of coil

$$dF_r = (T)\left(\mu_0 \frac{iT}{2L_c}\right)(i)(Rd\theta) = \frac{\mu_0}{2}(iT)^2\left(\frac{R}{L_c}\right)d\theta$$

Total instantaneous radial force acting on the coil, $F_r = \int_0^{2\pi} dF_r$

$$= \frac{\mu_0}{2}(iT)^2\left(\frac{R}{L_c}\right)\int_0^{2\pi} d\theta$$

$$= \frac{\mu_0}{2}(iT)^2\left(\frac{R}{L_c}\right)(2\pi)$$

$$= \frac{\mu_0}{2}(iT)^2\left(\frac{2\pi R}{L_c}\right)$$

$$= \frac{\mu_0}{2}(iT)^2\left(\frac{Lmt}{L_c}\right)$$

(b) Axial force

- Interaction of radial component of leakage flux with current carrying conductor produces force in axial direction.
- These forces tries to squeeze the winding together in middle. With symmetrical winding arrangement, these forces are negligible even under short circuit condition.
- In shell type transformer sandwich coil has symmetrical arrangement which will have force of repulsion between each pair.

Instantaneous mmf of winding $= iT_n$, Where $T_n =$ Number of turns in each half coil

Flux density in winding $= \mu_0 \mu_r H = \mu_0 \dfrac{iT_n}{W}$

Average flux density in winding $= \dfrac{\mu_0 \dfrac{iT_n}{W}}{2} = \mu_0 \dfrac{iT_n}{2W}$

Total axial force acting on the coil, $F_a = \left(T_n\right)\left(\mu_0 \frac{iT_n}{2W}\right)\left(i\right)\left(Lmt\right)$

$$= \frac{\mu_0}{2}\left(iT_n\right)^2\left(\frac{Lmt}{W}\right)$$

$$= \frac{\mu_0}{2}\left(i\frac{T}{2n}\right)^2\left(\frac{Lmt}{W}\right)$$

$$= \frac{\mu_0}{8n^2}\left(iT\right)^2\left(\frac{Lmt}{W}\right)$$

2.22. Effect of temperature rise on transformer

- Temperature rise in transformer is due to the conversion of loss developed in winding and core into the heat. Heat directed to the cooling medium by the way of radiation and convection.

(a) Temperature rise in tank with plain wall

- Tank wall dissipates heat by both radiation and conviction. A plain wall tank dissipates heat through radiation 6 W/m^2-^{o}C and through convection 6.5 W/m^2-^{o}C for temperature rise of 40 ^{o}C at an ambient temperature of 20 ^{o}C.

$$\text{Temperature Rise}, \theta = \frac{\text{Total loss}}{\text{Specific heat dissipation} \times \text{Heat dissipation surface of tank}}$$

$$= \frac{P_i + P_c}{\left(6.5+6\right)\times S_t}$$

$$= \frac{P_i + P_c}{12.5 S_t}$$

(b) Temperature rise in tank with tubes

- If temperature rise in tank with plain wall exceeds specific limit, additional tubes are attached with the wall to bring down the temperature.
- Additional tube will increase heat dissipation surface area, convection rate but will bring down the radiation rate.
- Hence there is no change by increased surface area so far as dissipation of heat is concern with radiation. But increase in heat dissipation is more effective in convection due to pressure difference created by oil in tubes.
- Let, dissipation surface area increased x times by tank surface area and convection rate by 35%.

l_t = Length of tube (m)

d_t = Diameter of tube (m)

a_t = Area of each tube (m^2)

n_t = Number of tube

Total area of tube = xS_t

Total heat dissipation area = $S_t + xS_t = (1+x)S_t$

Total heat dissipation by tank with tube $= (6.5+6)S_t + 1.35(6.5+0)(xS_t) = (12.5+8.8x)S_t$

Specific heat dissipated by tank with tube $= \dfrac{(12.5+8.8x)S_t}{(1+x)S_t} = \dfrac{(12.5+8.8x)}{(1+x)}$

$$\text{Temperature rise}, \theta = \frac{\text{Total loss}}{\text{Specific heat dissipation} \times \text{Heat dissipation surface}}$$

$$= \frac{P_i + P_c}{\dfrac{(12.5+8.8x)}{(1+x)} \times (1+x)S_t}$$

$$= \frac{P_i + P_c}{(12.5+8.8x)S_t}$$

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

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

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

$$= \frac{xS_t}{\pi d_t l_t}$$

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

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

2.23. Cooling methods used for oil immersed transformer

- To dissipate the heat to surroundings air and oil is used as coolant. Transformer using air as coolant is called dry type and oil as coolant is called oil immersed.
- The method of cooling depends upon the (i) medium of cooling (ii) Type of circulation employed. They are abbreviated with standard notation such as

  Air – A, Gas – G, Synthetic oil – L, Mineral oil – O, Solid insulation – S, Water – W

  Natural – N, Forced – F
- Coolant circulating inside the transformer comes in contact with winding and core, depending upon the method coolant transfers heat partially or fully to the tank walls from where it is dissipated to the surrounding medium.

(a) Oil natural air natural (ONAN)

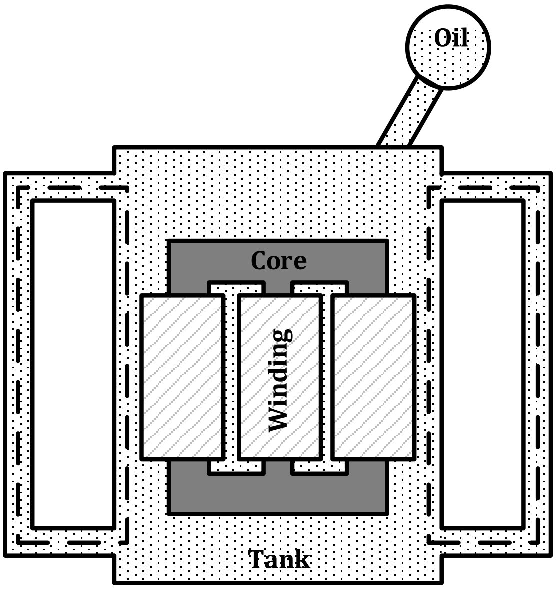

Figure 2. 18 Oil natural air natural (ONAN) cooling

- Air cooling is not sufficient and effective for medium and large size of transformer. Oil has main advantage of high heat conductivity and high co-efficient of volume expansion with temperature.
- Hence all transformers are immersed in oil and heat generated in windings and core are dissipated to the oil by conduction. In oil heat is transferred by convection. During convection heated oil transfers heat to the tank walls from where heat is taken away to the ambient air.
- During this process heated oil gets cooled and falls back to the bottom. Therefor natural thermal head is created which further transfer heat from heated part to the tank wall.
- Upto 30 kVA rating plain tank wall is sufficient to dissipate heat. Ratings higher than 30 kVA tank wall is increased by providing corrugations, fins, tubes and radiators.

(b) Oil natural air forced (ONAF)

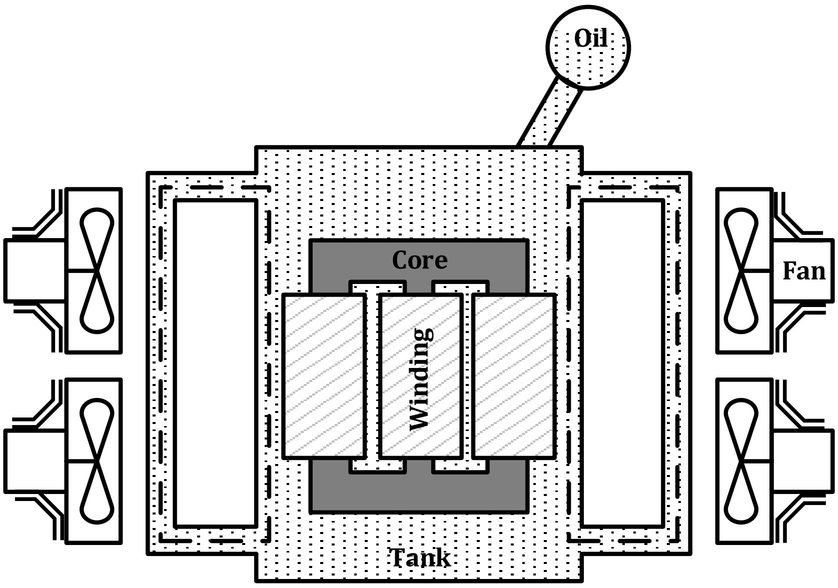

Figure 2. 19 Oil natural air forced (ONAF) Cooling

- Transformers are immersed in oil where oil circulation under natural head transfers heat towards the tank wall.
- In this type of cooling techniques, tank is made hollow and air is blown through it to cool transformer parts. Heat removal from inner tank wall is increased by 5-6 times the conventional means.
- However normal way by air blast is to use radiator banks of corrugated tubes separated from tank and cooled by air blast produced by fan.

(c) Oil natural water forced (ONWF)

- In this type of cooling techniques, copper cooling coils are mounted above the transformer core but below the oil surface.
- Main disadvantage of this method is it employs water inside the oil tank and water is at higher head than oil. In case of water leakage, it gets mixed with oil and reduces dielectric strength of oil.
- Water inlet and outlet pipes are insulated in order to prevent moisture from ambient air.

(d) Oil forced air forced (OFAF)

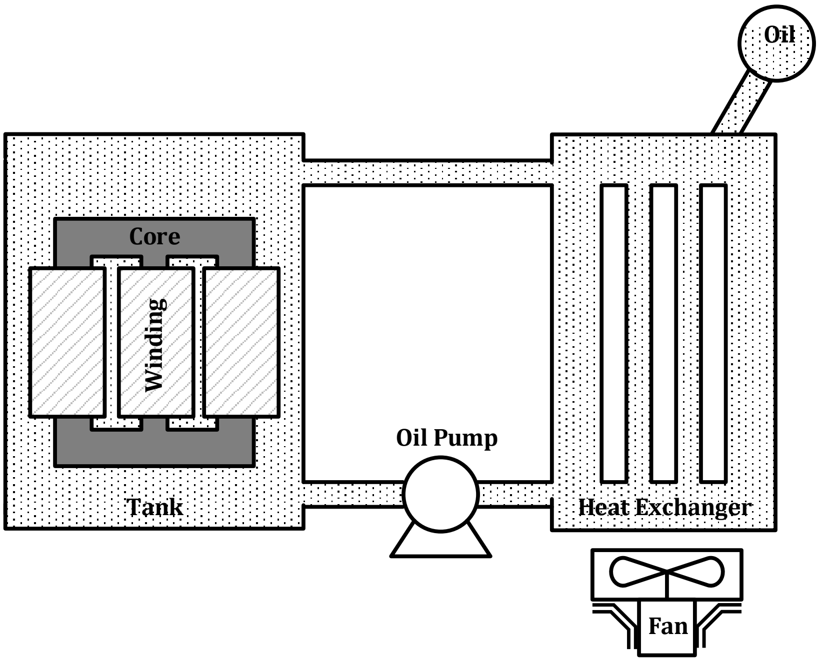

Figure 2. 20 Oil forced air forced (OFAF) cooling

- In large transformer natural oil circulation is not enough to cool transformer, hence forced circulation through oil pump is carried out.
- A motor driven oil pump circulates oil from transform tank to external heat exchanger to cool the oil.
- In oil forced air forced arrangement oil is cooled by external heat exchanger using air blast produced by fan.
- Oil pumps and fans are not used all the time but, they are switched ON by temperature sensors when temperature exceeds the limit.

(e) Oil forced water forced (OFWF)

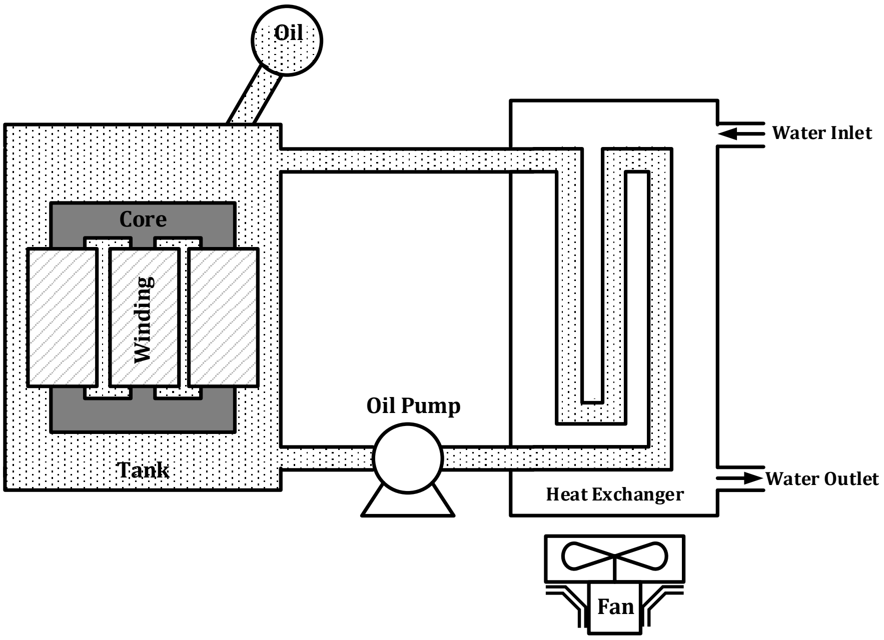

Figure 2. 21 Oil forced water forced (OFWF) cooling

- In this oil forced water forced method oil is cooled in water heat exchanger. This method is best suited where cooling water has large head.
- The pressure of oil is kept higher than that of water so if any leakage that occurs will be from oil to water only.
- Hydroelectric generating stations has large water availability, hence transformer with OFWF cooling method is used there.
