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

- Transformers
  - Based on Core
    - Core Type
  - Based on transformer Ratio
    - Step up
    - Step Down
  - Based on Service
    - Distribution Transformer
    - Power Transformer
Constructional Details
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, $E_t = \frac{E}{T} = 4.44f \phi_m$
Window in a 1φ transformer contains one primary & one secondary winding.

Window Space factor, \( K_w = \frac{A_c}{A_w} \)

Conductor area in window, \( A_c = K_w A_w \) \( \rightarrow (2) \)

Current Density \( (\delta) \) is same in both the windings

\( \delta = \frac{I_p}{a_p} = \frac{I_s}{a_s} \) \( \rightarrow (3) \)
**Output Equation of Transformer**

\[ a_p = \frac{I_p}{\delta} \quad ; \quad a_s = \frac{I_s}{\delta} \]

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

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

Total Cu. Area in window, \(A_c = \text{Cu.area of pry wdg} + \text{Cu.area of sec wdg}\)

\[
\begin{align*}
A_c &= T_p \ a_p + T_s \ a_s \\
&= T_p \ a_p + T_s \ a_s \\
&= T_p \frac{I_p}{\delta} + T_s \frac{I_s}{\delta} \\
&= \frac{1}{\delta} \left[ T_p I_p + T_s I_s \right] \\
&= \frac{1}{\delta} \left[ AT + AT \right] = \frac{2AT}{\delta} \rightarrow (5)
\end{align*}
\]
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,

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

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

\[ = E_t \Box AT \times 10^{-3} \rightarrow (6) \]

\[ = 4.44 f_{\phi_m} \frac{1}{2} K_w A_w \delta \times 10^{-3} \]

\[ = 2.22 f_{\phi_m} K_w A_w \delta \times 10^{-3} \]
We know that,

\[ B_m = \frac{\varphi_m}{A_i} \quad \text{and} \quad \varphi_m = B_m A_i \]

\[ Q = 2.22 f B_m A_i A_w K_w \delta \times 10^{-3} \text{ kVA} \]

Three phase transformer:

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

\[ A_c = 2T_p a_p + 2T_s a_s \]

\[ A_c = \frac{4 AT}{\delta} \rightarrow (7) \]

Compare (2) \& (7), \[ \frac{4 AT}{\delta} = K_w A_w \]

\[ AT = \frac{K_w A_w \delta}{4} \]
Output Equation of Transformer

kVA rating of 3φ transformer,

\[ Q = 3 \left( \frac{E_p}{T_p} P I_p \times 10^{-3} \right) \]

\[ = 3 \frac{E_p}{T_p} P I_p \times 10^{-3} \]

\[ = E_t \Delta AT \times 10^{-3} \]

\[ = 3 \times 4.44 \times f \phi_m \times \frac{1}{4} K_w A_w \delta \times 10^{-3} \]

\[ = 3.33 \int B_m A_i A_w K_w \delta \times 10^{-3} \text{ kVA} \]
EMF per Turn

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

Let,

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

\[
= 4.44 f \phi_m T_p I_p \times 10^{-3}
\]

\[
= 4.44 f \phi_m (AT) \times 10^{-3}
\]

\[
= 4.44 f \phi_m \frac{\phi_m}{r} \times 10^{-3}
\]

\[
\phi_m^2 = \frac{Q \cdot r}{4.44 f \times 10^{-3}} = \frac{Q \cdot r \times 10^3}{4.44 f}
\]

\[
\phi_m = \sqrt{\frac{Q \cdot r \times 10^3}{4.44 f}}
\]
EMF per Turn

\[ w.k.t, \ E_t = 4.44 \ f \ \varphi_m \]
\[ = 4.44 \ f \sqrt{\frac{Q \cdot r \times 10^3}{4.44 \ f}} = \sqrt{4.44 \ f} \cdot \sqrt{4.44 \ f} \cdot \sqrt{r \times 10^3} \cdot \sqrt{\frac{Q}{4.44 \ f}} \]
\[ = \sqrt{4.44 \ f \cdot r \times 10^3} \cdot \sqrt{Q} \]

*where, \( K = \sqrt{4.44 \ f \cdot r \times 10^3} \)*
\[ E_t = K \cdot \sqrt{Q} \]

\( K \) depends on the type, service condition & method of construction of transformer.
EMF per Turn

<table>
<thead>
<tr>
<th>Transformer Type</th>
<th>Value of K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1φ Shell Type</td>
<td>1.0 to 1.2</td>
</tr>
<tr>
<td>1φ Core Type</td>
<td>0.75 to 0.85</td>
</tr>
<tr>
<td>3φ Shell Type</td>
<td>1.2 to 1.3</td>
</tr>
<tr>
<td>3φ Core Type Distribution transformer</td>
<td>0.45 to 0.5</td>
</tr>
<tr>
<td>3φ Core Type Power transformer</td>
<td>0.6 to 0.7</td>
</tr>
</tbody>
</table>
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 \[ r = \frac{\varphi m}{AT} \]
Let us consider a single phase transformer.

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

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

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.

\[ r = \frac{\phi_m}{A T} \]

\[ \phi_m = B_m A_i \]

\[ A T = \frac{1}{2} K_w A_w \delta = \frac{A_c \delta}{2} \]
**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

\[ r = \frac{B_m A_i}{A_c \delta} = \frac{2 B_m A_i}{A_c \delta} \]

\[ r = \frac{A_i}{A_c} \cdot \frac{2 B_m}{\delta} \]

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

\( \beta \) is the function of \( r \) alone [\( \delta \) & \( B_m \) – Constant]

From (1) & (2),

\[ A_i = M \sqrt{\beta} \quad \land \quad A_c = \frac{M}{\sqrt{\beta}} \]

\[ := A_c A_i = M^2 \]
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,
\[
\eta_x = \frac{xQ}{xQ + P_i + x^2 P_c}
\]

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

\[
\frac{d\eta_x}{dx} = \frac{(xQ + P_i + x^2 P_c)Q - (Q + 2xP_c)xQ}{(xQ + P_i + x^2 P_c)^2} = 0
\]

\[
(xQ + P_i + x^2 P_c)Q = (Q + 2xP_c)xQ
\]

\[
\frac{(xQ + P_i + x^2 P_c)}{(xQ + P_i + x^2 P_c)} = (Q + 2xP_c)x
\]

\[
xQ + P_i + x^2 P_c = xQ + x^2 P_c + x^2 P_c
\]

\[
P_i = x^2 P_c
\]
Optimum Design

Design for Minimum Cost

\[ C_t = c_i g_i l_i A_i + c_c g_c L_{mt} A_c \]

where, \( c_i \) and \( c_c \) are specific costs of iron and copper respectively.

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

Differentiating \( C_t \) with respect to \( \beta \),

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

For minimum cost,

\[ \frac{d}{d\beta} C_t = 0 \]

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

\[ c_i g_i l_i = c_c g_c L_{mt} \frac{A_c}{A_i} \]
Optimum Design

Design for Minimum Cost

\[ c_i g_i l_i A_i = c_c g_c L_{mt} A_c \]

\[ c_i G_i = c_c G_c \]

\[ C_i = C_c \]

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

Similarly,

For minimum volume of transformer,

\[ G_i g_i = G_c g_c \text{ or } G_i G_c = g_i g_c \]

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

\[ P_i P_c = \frac{p_i G_i}{p_c G_c} \]

\[ x^2 = \frac{p_i G_i}{p_c G_c} \quad \text{or} \quad \frac{G_i}{G_c} = x^2 \frac{p_c}{p_i} \]

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)
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: \( \frac{\pi}{4} d^2 \)

Ratio of net core area to Area of Circumscribing circle is

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

Ratio of gross core area to Area of Circumscribing circle is

\[ \frac{0.5 d^2}{\frac{\pi}{4} d^2} = 0.64 \]
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, \( A_{gi} = \text{Area of square} = a^2 = \left( \frac{d}{\sqrt{2}} \right)^2 \)

\[ A_{gi} = 0.5d^2 \]

Let the stacking factor, \( S_f = 0.9 \)

Net core area, \( A_i = 0.9 \times 0.5d^2 = 0.45d^2 \)
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.
- \(\theta\) – 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 ‘\(\theta\)’
- For max value of ‘\(\theta\)’, \[
\frac{dA}{d\theta} = 0
\]
- From the figure,
  \[
  \cos \theta = \frac{a}{d} \Rightarrow a = d \cos \theta \\
  \sin \theta = \frac{b}{d} \Rightarrow b = d \sin \theta
  \]
Design of Core
Stepped Core or Cruciform Core

Two stepped core can be divided into 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 ‘\theta’,

\[ \frac{dA_{gi}}{d\theta} = 0 \]
Design of Core
Stepped Core or Cruciform Core

\[
\frac{dA}{d\theta} = d^2 2\cos^2 \theta - d^2 (2\sin \theta \cos \theta) \equiv 0
\]
i.e.,

\[
d^2 2\cos^2 \theta = d^2 (2\sin \theta \cos \theta)
\]
\[
2\cos^2 \theta = \sin 2\theta
\]
\[
\frac{\sin 2\theta}{\cos 2\theta} = 2
\]
\[
tan 2\theta = 2
\]
\[
2\theta = tan^{-1}(2)
\]
\[
\theta = \frac{1}{2} tan^{-1}(2) \equiv 31.72^0
\]

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

\[
\cos \theta = \frac{a}{d} \quad \therefore a = d \cos \theta = a = d \cos (31.72^0) = 0.85 \, d
\]
\[
\sin \theta = \frac{b}{d} \quad \therefore b = d \sin \theta = b = d \sin (31.72^0) = 0.53 \, d
\]
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 \( \times \) Gross Core area
\[ A_i = 0.9 \times 0.618d^2 = 0.56d^2 \]

The ratios,

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

\[ \frac{\text{Gross core area}}{\text{Area of Circumscribing circle}} = \frac{0.618d^2}{\frac{\pi d^2}{4}} = 0.79 \]
Core area factor, $K_C = \frac{\text{Net Core area}}{\text{Square of Circumscribing Circle}} = \frac{A_i}{d^2} = 0.56d^2 = 0.56$

Ratios of Multi-stepped Cores,

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Square Core</th>
<th>Cruciform Core</th>
<th>3-Stepped Core</th>
<th>4-Stepped Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross core area</td>
<td>0.64</td>
<td>0.79</td>
<td>0.84</td>
<td>0.87</td>
</tr>
<tr>
<td>Area of Circumscribing circle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net core area</td>
<td>0.58</td>
<td>0.71</td>
<td>0.75</td>
<td>0.78</td>
</tr>
<tr>
<td>Area of Circumscribing circle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core area factor, $K_C$</td>
<td>0.45</td>
<td>0.56</td>
<td>0.60</td>
<td>0.62</td>
</tr>
</tbody>
</table>
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

[Diagram with annotations for dimensions: H, W, d, Ww, D, Hw, Hy, d, D, H]
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.

\[
T_{LV} = \frac{V_{LV}}{E_t} \left( or \right) \frac{AT}{I_{LV}}
\]

where, \( V_{LV} = \) Rated voltage of LV winding
\( I_{LV} = \) Rated Current of LV winding
Design of Winding

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) Main tank

(b) Conservator & Breather

(c) Radiator

(d) Oil pump

(e) Fan motor

(f) Water outlet

(g) Water inlet
Transformer Winding
Transformer Winding

Disc coils

Helical coils

cross over coils
Insulations

- **Dry type Transformers:**
  - Varnish
  - Enamel

- **Large size Transformers:**
  - Unimpregnated paper
  - Cloths
  - Immersed in Transformer oil – insulation & coolent
## Comparison between Core & Shell Type

<table>
<thead>
<tr>
<th>Description</th>
<th>Core Type</th>
<th>Shell Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Easy to assemble &amp; Dismantle</td>
<td>Complex</td>
</tr>
<tr>
<td>Mechanical Strength</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Leakage reactance</td>
<td>Higher</td>
<td>Smaller</td>
</tr>
<tr>
<td>Cooling</td>
<td>Better cooling of Winding</td>
<td>Better cooling of Core</td>
</tr>
<tr>
<td>Repair</td>
<td>Easy</td>
<td>Hard</td>
</tr>
<tr>
<td>Applications</td>
<td>High Voltage &amp; Low output</td>
<td>Low Voltages &amp; Large Output</td>
</tr>
</tbody>
</table>
## Classification on Service

<table>
<thead>
<tr>
<th>Details</th>
<th>Distribution transformer</th>
<th>Power Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Upto 500kVA</td>
<td>Above 500kVA</td>
</tr>
<tr>
<td>Voltage rating</td>
<td>11,22,33kV/440V</td>
<td>400/33kV;220/11kV…</td>
</tr>
<tr>
<td>Connection</td>
<td>Δ/Y, 3φ, 4 Wire</td>
<td>Δ/Δ; Δ/Y, 3φ, 4 Wire</td>
</tr>
<tr>
<td>Flux Density</td>
<td>Upto 1.5 wb/m²</td>
<td>Upto 1.7 wb/m²</td>
</tr>
<tr>
<td>Current Density</td>
<td>Upto 2.6 A/mm²</td>
<td>Upto 3.3 A/mm²</td>
</tr>
<tr>
<td>Load</td>
<td>100% for few Hrs, Part load for some time, No-load for few Hrs</td>
<td>Nearly on Full load</td>
</tr>
<tr>
<td>Ratio of Iron Loss to Cu loss</td>
<td>1:3</td>
<td>1:1</td>
</tr>
<tr>
<td>Regulation</td>
<td>4 to 9%</td>
<td>6 to 10%</td>
</tr>
<tr>
<td>Cooling</td>
<td>Self oil cooled</td>
<td>Forced Oil Cooled</td>
</tr>
</tbody>
</table>
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°C above the ambient temperature of 20°C, the heat dissipations are as follows:
  - Specific heat dissipation by radiation, \( \lambda_{\text{rad}} = 6 \text{ W/m}^2\text{.C} \)
  - Specific heat dissipation by convection, \( \lambda_{\text{conv}} = 6.5 \text{ W/m}^2\text{.C} \)
  - Total heat dissipation in plain wall 12.5 W/m\(^2\).C

\( S_t \) – 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

特定的热量散失由于对流是，

\[ \lambda_{\text{conv}} = 40.3 \left( \frac{\theta}{H} \right)^{14} \text{W/m}^2\cdot{}^0\text{C} \]

where, \( \theta \) - Temperature difference of the surface relative to oil, \( {}^0\text{C} \)
\( H \) - Height of dissipating surface, m

- The average working temperature of oil is 50-60\(^0\text{C}\).

- For \( \theta = 20^0\text{C} \land H = 0.5 \) to \( 1 \) m,
  \[ \lambda_{\text{conv}} = 80 \) to \( 100 \text{ W/m}^2\cdot{}^0\text{C} \).

The value of the dissipation in air is 8 \text{ W/m}^2\cdot{}^0\text{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 be proportional to increase in area. Because, the tubes prevent 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

$$6.5 \times \frac{13.5}{100} \times XS_t = 8.8 XS_t$$

Total loss dissipated by walls and tubes

$$12.5 S_t + 8.8 XS_t = (12.5 + 8.8X)S_t \rightarrow (1)$$

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

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

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

Temperature rise in Transformer with cooling tubes

\[ \theta = \frac{\text{Total loss}}{\text{Loss Dissipated}} \]

Total losses, \( P_{\text{loss}} = P_i + P_c \) \( \cdots \) (3) From (1) and (3), we have, \[ \theta = \frac{P_i + P_c}{S_t (12.5 + 8.8X)} = \frac{12.5 + 8.8X}{\theta S_t} = \frac{P_i + P_c}{\theta S_t} - 12.5 \]

\[ \begin{align*}
X &= \frac{1}{8.8} \left( \frac{P_i + P_c}{\theta S_t} - 12.5 \right)
\end{align*} \]
Design of tanks with cooling tubes

Total area of cooling tubes

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

\[ S_t = \frac{1}{8.8} \left( \frac{P_i + P_c}{\theta} - 12.5S_t \right) \rightarrow (5) \]

Let, \( l_t \) – Length of tubes

\( d_t \) – Diameter of tubes

\[ \therefore \text{Surface area of tubes} = \pi d_t l_t \]

Total number of tubes, \( n_t \)

\[ n_t = \frac{\text{Total area of tubes}}{\text{Area of each tube}} \]

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

- Standard diameter of cooling tube is 50mm & length depends on the height of the tank.
- Center to center spacing is 75mm.
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, \( W_T = 2D + D_{oc} + 2C_1 \) (For 3\( \phi \) Transformer)

\[ = D + D_{oc} + 2C_1 \] (For 1\( \phi \) Transformer)

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

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.
<table>
<thead>
<tr>
<th>Voltage kV</th>
<th>KVA Rating</th>
<th>Clearance mm</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>b or c1</td>
<td>l or c2</td>
</tr>
<tr>
<td>11 kV or less</td>
<td>Less than 1000</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>About 11 kV</td>
<td>1000 to 5000</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>and upto 33 kV</td>
<td>Less than 1000</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>1000 to 5000</td>
<td>85</td>
<td>125</td>
</tr>
</tbody>
</table>
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 \( S_t = 2(1 + 0.5) \times 1.25 = 3.75 \text{ m}^2 \)

Let the tube area be \( x S_t \).

\[
\therefore \text{Total dissipating surface} = (1 + x) S_t = 3.75 (1 + x)
\]

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

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

\[
\frac{12.5 + 8.8x}{1 + x} = \frac{36.5}{1 \times x}
\]

\[
\text{or} \quad x = 2.73
\]

\[
\therefore \text{Area of tubes} = 2.73 \times 3.75 = 10.23 \text{ m}^2.
\]

Wall area of each tube = \( \pi d_t l_t = \pi \times 0.05 \times 1.05 = 0.165 \text{ m}^2 \).

\[
\therefore \text{Total number of tubes to be provided} = 10.23/0.165 = 62.
\]
.: 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 = 2\( l_c \)

Total Length of the yoke = 2\( l_y \)

Here, \( l_c = H_w = \)Height of Window

\[
l_y = W_w = \text{Width of Window}
\]

MMF for core=MMF per metre for max. flux density in core \( X \) Total length of Core

\[
= \text{at}_c \times 2l_c = 2 \times \text{at}_c l_c
\]

MMF for yoke=MMF per meter for max. flux density in yoke \( X \) Total length of yoke

\[
= \text{at}_y \times 2l_y = 2 \times \text{at}_y l_y
\]

Total Magnetizing MMF,\( AT_0 = \)MMF for Core+MMF for Yoke+MMF for joints

\[
= 2 \times \text{at}_c l_c + 2 \times \text{at}_y l_y + \text{MMF for joints}
\]

The values of \( \text{at}_c \) & \( \text{at}_y \) are taken from B-H curve of transformer steel.
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

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

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

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