Transformer Design
(© Dr. R. C. Goel & Nafees Ahmed)

By

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References:
1. Notes by Dr. R. C. Goel
2. Electrical Machine Design by A.K. Sawhney
4. VTU e-Learning
5. www.goole.com
6. www.wikipedia.org
**OUTPUT EQUATION:** It gives the relationship between electrical rating and physical dimensions of the machines.

Let

\[ V_1 = \text{Primary voltage say LV} \]
\[ V_2 = \text{Secondary voltage say HV} \]
\[ I_1 = \text{Primary current} \]
\[ I_2 = \text{Secondary current} \]
\[ N_1 = \text{Primary no of turns} \]
\[ N_2 = \text{Secondary no of turns} \]
\[ a_1 = \text{Sectional area of LV conductors (m}^2) \]
\[ a_2 = \text{Sectional area of HV conductors (m}^2) \]
\[ \delta = \text{Permissible current density (A/m}^2) \]
\[ Q = \text{Rating in KVA} \]

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

1) **For 1-phase core type transformer**

Rating is given by

\[ Q = V_1 I_1 \times 10^{-3} \quad \text{KVA} \]
\[ = (4.44 f \phi_m N_1) I_1 \times 10^{-3} \quad \text{KVA} \]
\[ = 4.44 f (A_B m) N_1 I_1 \times 10^{-3} \quad \text{KVA} \]

\[ (\therefore V_1 = 4.44 f \phi_m N_1) \]
\[ (\therefore \phi_m = A_B m) \]

Where

\[ f = \text{frequency} \]
\[ \phi_m = \text{Maximum flux in the core} \]
\[ A_i = \text{Sectional area of core} \]
\[ B_m = \text{Maximum flux density in the core} \]

Window Space Factor

\[ K_w = \frac{\text{Actual Cu Section Area of Windings in Window}}{\text{Window Area (}A_w)} \]
\[ = \frac{a_1 N_1 + a_2 N_2}{A_w} \]
\[ = \frac{(I_1/\delta) N_1 + (I_2/\delta) N_2}{A_w} \]
\[ = \frac{I_1 N_1 + I_2 N_2}{\delta A_w} \]
\[ = \frac{2I_1 N_1}{\delta A_w} \]

\[ (\text{For Ideal Transformer} \ I_1 N_1 = I_2 N_2) \]

So
\[ N_1 I_1 = \frac{\delta K_w A_w}{2} \]  \hspace{2cm} \text{--- (2)}

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

\[
Q = 4.44 f A_i B_m \frac{\delta K_w A_w}{2} \times 10^{-3} \quad \text{KVA}
\]

\[
Q = 2.22 f A_i B_m \delta K_w A_w \times 10^{-3} \quad \text{KVA}
\]  \hspace{2cm} \text{--- (3)}

(2) \hspace{1cm} \text{For 1-phase shell type transformer}

Window Space Factor

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

\[
= \frac{(I_1/\delta) N_1 + (I_2/\delta) N_2}{A_w} \quad \text{(:} \ a_1 = I_1/\delta \text{ & } a_2 = I_2/\delta \text{)}
\]

\[
= \frac{I_1 N_1 + I_2 N_2}{\delta A_w}
\]

\[
= \frac{2I_1 N_1}{\delta A_w} \quad \text{(For Ideal Transformer } I_1N_1 = I_2N_2 \text{)}
\]

So

\[
N_1 I_1 = \frac{\delta K_w A_w}{2} \]  \hspace{2cm} \text{--- (4)}

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

\[
Q = 4.44 f A_i B_m \frac{\delta K_w A_w}{2} \times 10^{-3} \quad \text{KVA}
\]

\[
Q = 2.22 f A_i B_m \delta K_w A_w \times 10^{-3} \quad \text{KVA} \]  \hspace{2cm} \text{--- (5)}

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

(3) \hspace{1cm} \text{For 3-phase core type transformer}

Window Space Factor

Rating is given by

\[
Q = 3 \times V_i I_i \times 10^{-3} \quad \text{KVA}
\]

\[
= 3 \times (4.44 f \phi_m N_1) I_i \times 10^{-3} \quad \text{KVA} \]

\[
= 3 \times (4.44 f A_i B_m N_1) I_i \times 10^{-3} \quad \text{KVA} \]  \hspace{2cm} \text{--- (6)}

\[ \because \ V_i = 4.44 f \phi_m N_1 \]

\[ \because \ \phi_m = A_i B_m \]
\[ K_w = \frac{Actual\ Cu\ Section\ Area\ of\ Windings\ in\ Window}{Window\ Area\ (A_w)} \]

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

\[ = \frac{2 \times [(I_1/\delta)N_1 + (I_2/\delta)N_2]}{A_w} \quad (\because a_1 = I_1/\delta\ &\ a_2 = I_2/\delta) \]

\[ = \frac{2I_1N_1 + I_2N_2}{\delta A_w} \]

\[ = \frac{2I_1N_1}{\delta A_w} \quad (For\ Ideal\ Transformer\ I_1N_1 = I_2N_2) \]

So

\[ N_1I_1 = \frac{\delta K_w A_w}{4} \quad (7) \]

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

\[ Q = 3 \times 4.44 \times f \times A_i \times B_m \times \frac{\delta K_w A_w}{4} \times 10^{-3} \quad KVA \]

\[ Q = 3.33 \times f \times A_i \times B_m \times \delta K_w A_w \times 10^{-3} \quad KVA \quad (8) \]

(3) For 3-phase shell type transformer

Window Space Factor

\[ K_w = \frac{a_1N_1 + a_2N_2}{A_w} \]

\[ = \frac{(I_1/\delta)N_1 + (I_2/\delta)N_2}{A_w} \quad (\because a_1 = I_1/\delta\ &\ a_2 = I_2/\delta) \]

\[ = \frac{I_1N_1 + I_2N_2}{\delta A_w} \]

\[ = \frac{2I_1N_1}{\delta A_w} \quad (For\ Ideal\ Transformer\ I_1N_1 = I_2N_2) \]

So

\[ N_1I_1 = \frac{\delta K_w A_w}{2} \quad (9) \]

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

\[ Q = 3 \times 4.44 \times f \times A_i \times B_m \times \frac{\delta K_w A_w}{2} \times 10^{-3} \quad KVA \]

\[ Q = 6.66 \times f \times A_i \times B_m \times \delta K_w A_w \times 10^{-3} \quad KVA \quad (10) \]
CHOICE OF MAGNETIC LOADING ($B_m$)

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

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

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

CHOICE OF ELECTRIC LOADING ($\delta$)
This depends upon cooling method employed

1. Natural Cooling: 1.5—2.3 A/mm$^2$
   - AN  Air Natural cooling
   - ON  Oil Natural cooling
   - OFN Oil Forced circulated with Natural air cooling

2. Forced Cooling: 2.2—4.0 A/mm$^2$
   - AB  Air Blast cooling
   - OB  Oil Blast cooling
   - OFB Oil Forced circulated with air Blast cooling

3. Water Cooling: 5.0—6.0 A/mm$^2$
   - OW  Oil immersed with circulated Water cooling
   - OFW Oil Forced with circulated Water cooling

CORE CONSTRUCTION:

(a) U-I type

(b) E-I type

(c) U-T type

(d) L-L type
EMF PER TURN:

We know
\[ V_1 = 4.44 f \phi_m N_1 \]

So EMF/turn \[ E_i = \frac{V_1}{N_1} = 4.44 f \phi_m \]

and
\[ Q = V_1 I_1 \times 10^{-3} \quad \text{KVA} \]  \[(\text{Note: Take Q as per phase rating in KVA)}\]
\[ = (4.44 f \phi_m N_1) I_1 \times 10^{-3} \quad \text{KVA} \]
\[ = E_i N_1 I_1 \times 10^{-3} \quad \text{KVA} \]

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

Magnetic loading \[ = \phi_m \]

Electric loading \[ = N_1 I_1 \]

So \[ \frac{\phi_m}{N_1 I_1} = \text{const} \text{tan}(\text{say } \theta) \] \[ \Rightarrow N_1 I_1 = \frac{\phi_m}{r} \] put in equation (3)

\[ Q = E_i \frac{\phi_m}{r} \times 10^{-3} \quad \text{KVA} \]

Or \[ Q = E_i \frac{E_i}{4.44 f r} \times 10^{-3} \quad \text{KVA} \]

using equation (2)

\[ E_i^2 = (4.44 f r \times 10^{-3}) \times Q \]

Or \[ E_i = K_t \sqrt{Q} \quad \text{Volts/turn} \]

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

\[ K_t = 0.6 \text{ to } 0.7 \] for 3-phase core type power transformer
\[ K_t = 0.45 \] for 3-phase core type distribution transformer
\[ K_t = 1.3 \] for 3-phase shell type transformer
\[ K_t = 0.75 \text{ to } 0.85 \] for 1-phase core type transformer
\[ K_t = 1.0 \text{ to } 1.2 \] for 1-phase shell type transformer

ESTIMATION OF CORE X-SECTIONAL AREA \( A_i \)
We know
\[ E_i = K_i \sqrt{Q} \]
\[ E_i = 4.44 f \phi_m \]
Or \[ E_i = 4.44 f A B_m \]
So \[ A_i = \frac{E_i}{4.44 f B_m} \]

Now the core may be following types

1-Step Core
2-Step Core
3-Step Core
4-Step Core

K=
0.45
0.56
0.60
0.625

\(d\) = Diameter of circumscribe circle

For Square core

Gross Area \(= \frac{d}{\sqrt{2}} \times \frac{d}{\sqrt{2}} = 0.5 d^2\)

Let stacking factor \(K_i = 0.9\)

Actual Iron Area
\[ A_i = 0.9 \times 0.5 d^2 \]
\[ = 0.45 d^2 \]
\(\text{Or} \quad A_i = K d^2 \)

So \[ A_i = K d^2 \]
\(\text{Or} \quad d = \sqrt[2]{\frac{A}{K}} \)

Graphical method to calculate dimensions of the core

Consider 2 step core

\(\theta = \frac{90^\circ}{n + 1}, \quad n = \text{No of Steps}\)
\(i.e \; n = 2\)
\(\theta = \frac{90^\circ}{2 + 1} = 30^\circ\)
\(So \quad a = d \cos \theta \)
\(b = d \sin \theta \)

Percentage fill
\[ = \frac{\text{Gross Area of Stepped core}}{\text{Area of circuncircle}} = \frac{K d^2 / K_i}{\pi d^2 / 4} \]
\[ \frac{0.625d^2}{0.9} \] for 4 Step core

\[ = \frac{\Pi}{4}(d^2) \]

= 0.885 or 88.5%

<table>
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<th>No of steps</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>84.9%</td>
<td>88.5%</td>
<td>90.8%</td>
<td>92.3%</td>
<td>93.4%</td>
<td>94.8%</td>
<td>95.8%</td>
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**ESTIMATION OF MAIN DIMENSIONS:**

Consider a 3-phase core type transformer

We know output equation

\[ Q = 3.33 f A_i B_m \delta K_w A_w \times 10^{-3} \text{ KVA} \]

So, Window area

\[ A_w = \frac{Q}{3.33 f A_i B_m \delta K_w \times 10^{-3}} \text{ m}^2 \]

where

\[ K_w = \begin{cases} 8 & \text{for upto 10 KVA} \\ \frac{10}{30 + \text{HigherKV}} & \text{for upto 200 KVA} \\ \frac{12}{30 + \text{HigherKV}} & \text{for upto 1000 KVA} \end{cases} \]

For higher rating \( K_w = 0.15 \text{ to } 0.20 \)

Assume some suitable range for \( D = (1.7 \text{ to } 2) \text{ d} \)

Width of the window \( W_w = D - 0.9d \)

Height of the window

\[ L = \frac{A_w}{\text{width of window}(W_w)} \]

\( \therefore L \times W_w = A_w \)
Generally \( \frac{L}{W_w} = 2 \) to 4

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

\[
\begin{align*}
A_y &= (1.10 \text{ to } 1.15) \ A_i \\
\text{Depth of yoke} & \quad D_y = a \\
\text{Height of the yoke} & \quad h_y = A_y/D_y \\
\end{align*}
\]

\[
\begin{align*}
\text{Width of the core} & \quad W = 2* D + 0.9 \ d \\
& \quad \text{Or } W=2W_w+3\times0.9d \quad (\text{As } W_w = D-0.9d) \\
\text{Height of the core} & \quad H = L + 2*h_y
\end{align*}
\]

Flux density in yoke

\[
B_y = \frac{A_i}{A_y} B_m
\]

\underline{ESTIMATION OF CORE LOSS AND CORE LOSS COMPONENT OF NO LOAD CURRENT I_c:}

Volume of iron in core

\[
= 3* L^* A_i \quad m^3
\]

Weight of iron in core

\[
= \text{density} \times \text{volume} \\
= \rho_i \times 3* L^* A_i \quad Kg
\]

\( \rho_i = \text{density of iron (kg/m}^3) \)

\( =7600 \text{ Kg/m}^3 \text{ for normal Iron/steel} \)

\( =6500 \text{ Kg/m}^3 \text{ for M-4 steel} \)

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

So

Iron loss in core

\[
= p_{\text{core}} \times \rho_i \times 3* L^* A_i \quad \text{Watt}
\]

Similarly

Iron loss in yoke

\[
= p_{\text{yoke}} \times \rho_i \times 2* W^* A_y \quad \text{Watt}
\]

Where

\( p_{\text{yoke}} = \text{specific iron loss corresponding to flux density } B_y \text{ in yoke} \)

Total Iron loss

\[
P_i = \text{Iron loss in core} + \text{Iron loss in yoke}
\]

Core loss component of no load current

\[
I_c = \text{Core loss per phase/ Primary Voltage} \\
I_c = \frac{P_i}{3V_i}
\]

\underline{ESTIMATION OF MAGNETIZING CURRENT OF NO LOAD CURRENT I_m:}
Find out magnetizing force \( H \) (at core, at/m) corresponding to flux density \( B_m \) in the core and at yoke corresponding to flux density in the yoke from B-H curve

\[
(B_m \Rightarrow \text{at core/m}, \quad B_e \Rightarrow \text{at yoke/m})
\]

So

MMF required for the core \( = 3L \times \text{at core} \)
MMF required for the yoke \( = 2W \times \text{at yoke} \)

We account 5% AT for joints etc
So total MMF required \( = 1.05[\text{MMF for core + MMF for yoke}] \)

Peak value of the magnetizing current

\[
I_{m, \text{peak}} = \frac{\text{Total MMF required}}{3N_1}
\]

RMS value of the magnetizing current

\[
I_{m, \text{RMS}} = \frac{I_{m, \text{peak}}}{\sqrt{2}}
\]

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

**ESTIMATION OF NO LOAD CURRENT AND PHASOR DIAGRAM:**

No load current \( I_0 \)

\[
I_0 = \sqrt{I_c^2 + I_m^2}
\]

No load power factor

\[
\text{Cos} \phi_o = \frac{I_c}{I_o}
\]

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

**ESTIMATION OF NO OF TURNS ON LV AND HV WINDING**

Primary no of turns \( \quad N_1 = \frac{V_1}{E_t} \)

Secondary no of turns \( \quad N_2 = \frac{V_2}{E_t} \)

**ESTIMATION OF SECTIONAL AREA OF PRIMARY AND SECONDARY CONDUCTORS**
Primary current
\[ I_1 = \frac{Q \times 10^{-3}}{3V_1} \]

Secondary current
\[ I_2 = \frac{Q \times 10^{-3}}{3V_2} \quad OR \quad \frac{N_1}{N_2} I_1 \]

Sectional area of primary conductor
\[ a_1 = \frac{I_1}{\delta} \]

Sectional area of secondary conductor
\[ a_2 = \frac{I_2}{\delta} \]

Where \( \delta \) is current density.

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

**DETERMINATION OF R_1 & R_2 AND CU LOSSES:**

Let \( L_{mt} = \) Length of mean turn

Resistance of primary winding
\[ R_{1, \text{dc}, 75^\circ} = 0.021 \times 10^{-6} \frac{L_{mt} N_1(m)}{a_1(m^2)} \]

Resistance of secondary winding
\[ R_{2, \text{dc}, 75^\circ} = 0.021 \times 10^{-6} \frac{L_{mt} N_2(m)}{a_2(m^2)} \]

Copper loss in primary winding
\[ = 3I_1^2 R_1 \quad \text{Watt} \]

Copper loss in secondary winding
\[ = 3I_2^2 R_2 \quad \text{Watt} \]

Total copper loss
\[ = 3I_1^2 R_1 + 3I_2^2 R_2 \]
\[ = 3I_1^2 (R_1 + R_2) \]
\[ = 3I_1^2 R_p \]

Where
\[ R_{01} = R_p = R_1 + R_2 \]

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

**DETERMINATION OF EFFICIENCY:**

Efficiency
\[ \eta = \frac{\text{Output Power}}{\text{Input Power}} \]

\[ \eta = \frac{\text{Output Power}}{\text{Output Power} + \text{Losses}} \]

\[ \eta = \frac{\text{Output Power}}{\text{Output Power} + \text{Iron Loss} + \text{Cu loss}} \times 100 \% \]

**ESTIMATION OF LEAKAGE REACTANCES(X_1 & X_2):**
Assumptions
1. Consider permeability of iron as infinity that is MMF is needed only for leakage flux path in the window.
2. The leakage flux lines are parallel to the axis of the core.

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

MMF at distance x

\[ M_x = \frac{N_1 I_1}{b_1} x \]

Permeance of this elementary cylinder

\[ = \mu_o \frac{A}{L} \]

\[ = \mu_o \frac{L_{ml} dx}{L_c} \quad (L_c = \text{Length of winding} \approx 0.8L) \]

\[ \therefore S = \frac{1}{\mu_o A} \quad \& \quad \text{Permeance} = \frac{1}{S} \]

Leakage flux lines associated with elementary cylinder

\[ d\phi_x = M_x \times \text{Permeance} \]

\[ = \frac{N_1 I_1}{b_1} x \times \mu_o \frac{L_{ml} dx}{L_c} \]

Flux linkage due to this leakage flux

\[ d\psi_x = \text{No of turns with which it is associated} \times d\phi_x \]

\[ = \frac{N_1 I_1}{b_1} \times \frac{N_1 I_1}{b_1} x \times \mu_o \frac{L_{ml} dx}{L_c} \]

\[ = \mu_o N_1^2 \frac{L_{ml}}{L_c} I_1 \left( \frac{x}{b_1} \right)^2 dx \]

Flux linkages (or associated) with primary winding

\[ \psi_1 = \mu_o N_1^2 \frac{L_{ml}}{L_c} I_1 \left( \frac{x}{b_1} \right)^2 \left. dx \right|_0^{b_1} = \mu_o N_1^2 \frac{L_{ml}}{L_c} I_1 \left( \frac{b_1}{3} \right) \]

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

\[ \psi_o = \mu_o N_1^2 \frac{L_{ml}}{L_c} I_1 a \]

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

\[ \psi_1 = \psi_1 + \frac{\psi_o}{2} \]

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

Similarly total flux linkages with secondary winding
\[ \psi_2 = \psi_2' + \frac{\psi_o}{2} \]

\[ \psi_2 = \mu_o N_2^2 \frac{L_{mt}}{L_c} I_2 \left( \frac{b_2}{3} + \frac{a}{2} \right) \]

Primary & Secondary leakage inductance

\[ L_1 = \frac{\psi_1}{I_1} = \mu_o N_1^2 \frac{L_{mt}}{L_c} \left( \frac{b_1}{3} + \frac{a}{2} \right) \]

\[ L_2 = \frac{\psi_2}{I_2} = \mu_o N_2^2 \frac{L_{mt}}{L_c} \left( \frac{b_2}{3} + \frac{a}{2} \right) \]

Primary & Secondary leakage reactance

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

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

Total Leakage reactance referred to primary side

\[ X_{01} = X_p = X_1 + X_2 = 2\pi f \mu_o N_1^2 \frac{L_{mt}}{L_c} \left( \frac{b_1 + b_2}{3} + a \right) \]

Total Leakage reactance referred to secondary side

\[ X_{02} = X_s = X'_1 + X_2 = 2\pi f \mu_o N_2^2 \frac{L_{mt}}{L_c} \left( \frac{b_1 + b_2}{3} + a \right) \]

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

**Note:** How to control \( X_p \)?

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

**CALCULATION OF VOLTAGE REGULATION OF TRANSFORMER:**

\[ V.R. = \frac{I_2 R_{o2} \cos \phi_2 + I_2 X_{o2} \sin \phi_2}{E_2} \times 100 \]

\[ = \frac{R_{o2} \cos \phi_2}{E_2 / I_2} \times 100 \pm \frac{X_{o2} \sin \phi_2}{E_2 / I_2} \times 100 \]

\[ = \% R_{o2} \cos \phi_2 \pm \% X_{o2} \sin \phi_2 \]

**TRANSFORMER TANK DESIGN:**

Width of the transformer (Tank)

\[ W_t = 2D_t + D_e + 2b \]

Where

\( D_e = \) External diameter of HV winding

\( b = \) Clearance width wise between HV and tank

Depth of transformer (Tank)

\[ D_t = D_e + 2a \]

Where

\( a = \) Clearance depth wise between HV and tank

Height of transformer (Tank)

\[ H_t = H + h \]

Where

\( h = h_1 + h_2 = \) Clearance height wise of top and bottom
CALCULATION OF TEMPERATURE RISE:

Tank of a 3-Phase transformer
Surface area of 4 vertical side of the tank (Heat is considered to be dissipated from 4 vertical sides of the tank)

\[ S_t = 2(W_t + D_t) H_t \text{ m}^2 \]  
(Excluding area of top and bottom of tank)

Let

\[ \theta = \text{Temp rise of oil (35° C to 50° C)} \]

\[ 12.5S_t \theta = \text{Total full load losses (Iron loss + Cu loss)} \]

So temp rise in °C \[ \theta = \frac{\text{Total full load losses}}{12.5 \times S_t} \]

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

**CALCULATION OF NO OF COOLING TUBES:**

Let \[ xS_t = \text{Surface area of all cooling tubes} \]

Then

\[ \text{Losses to be dissipated by the transformer walls and cooling tube} = \frac{\text{Total losses}}{12.5 \times S_t} \]

\[ (12.5 \times S_t + 8.5 \times xS_t) \theta = \text{Total losses} \]

<table>
<thead>
<tr>
<th>Specific Heat dissipation</th>
<th>6 Watt/m(^2)-0°C by Radiation</th>
<th>6.5 Watt/m(^2)-0°C by Convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 W-Raditon+6.5 W-Convection=12.5</td>
<td>6.5*1.35 W = 8.5 (≈ 35% more) Convection only</td>
<td></td>
</tr>
</tbody>
</table>

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

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

\[ A_t = \text{Surface area of one cooling tube} = \pi d_{\text{tube, mean}} \]

Hence

No of cooling tubes \[ = \frac{xS_t}{A_t} \]

\[ d = 5 \text{ Cm} \]

Tank and Arrangement of Cooling tubes

**WEIGHT OF TRANSFORMER:**

15 | [http://eedofdit.weebly.com](http://eedofdit.weebly.com) © Nafees Ahmed
Let

\( W_i = \text{Weight of Iron in core and yoke (core volume} \times \text{density} + \text{yoke volume} \times \text{density) Kg} \)

\( W_c = \text{Weight of copper in winding (volume} \times \text{density) Kg} \)

(density of cu = 8900 Kg/m\(^3\))

Weight of Oil

= Volume of oil * 880 Kg

Add 20% of (\( Wi + W_c \)) for fittings, tank etc.

Total weight is equal to weight of above all parts.

**Example 1:** Estimate the main core dimensions for a 50 Hz, 3-phase, 200 KVA, 6600/500 V, Star/mesh connected core type transformer. Use the following data:

Core limb section to be 4-stepped for which the area factor =0.62

Window space factor =0.27

Current density = 2.8 MA/m\(^2\)

Volts per turn = 8.5

Maximum flux density = 1.25 Wb/m\(^2\).

**Solution:**

We know emf per turn

\[
E_r = 4.44 f A_i B_m \Rightarrow 8.5 = 4.44 \times 50 \times A_i \times 1.25 \Rightarrow A_i = 0.03063 \text{ m}^2
\]

\[
\Rightarrow d = 0.2214 \text{ m}
\]

For 4 stepped core

\[
A_i = K d^2 \Rightarrow 0.03063 = 0.625 d^2 \Rightarrow d = 0.2214 \text{ m}
\]

We also know

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

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

\[
\Rightarrow A_w = 0.0415 \text{ m}^2 = L x W_w \quad \text{-------- (1)}
\]

\[
\frac{L}{W_w} = 2 \quad \text{-------- (2)}
\]

Solving (1) & (2)

\[
W_w = 0.144 \text{ m}
\]

\[
L = 0.288 \text{ m}
\]

\[
A_y = 1.15 A_i \quad \text{(Let yoke area} A_y \text{ is 15% more than area} A_i
\]

\[
D_y = a \quad \text{(Width of largest stamping)}
\]

\[
d = d \cos \Theta
\]

\[
A_y = 0.92 d \quad \text{(To give maximum area} A_i
\]

\[
D_y = 0.204 \text{ m}
\]

Selecting

\[
D_y = 0.92 d \quad \text{(Assuming} A_y = 15\% \text{ more than} A_i
\]

\[
h_y = A_y/D_y = 1.15 A_i/D_y
\]

\[
= 1.15 \times 0.03063/0.204
\]

\[
\Rightarrow h_y = 0.173 \text{ m}
\]

Overall height

\[
H = L + h_y = 0.288 + 0.173 \Rightarrow H = 0.461 \text{ m}
\]
Example 2: Calculate no load current of a 400 V, 50 Hz, 1-Phase, core type transformer, the particulars of which are as follows:
Length of means magnetic path =200 Cm,
Gross core section =100 Cm²,
Joints equivalent to 0.1 mm air gap,
Maximum flux density =0.7 T,
Specific core loss at 50 Hz & 0.7 T =0.5 W/Kg,
Ampere turns =2.2 per cm for 0.7 T,
Stacking factor =0.9,
Density of core material = 7.5x 10⁳ Kg/m³.
Solution: Find $I_{C}$:

Core loss component of no load current $I_{C} = \frac{\text{Total core loss}}{V_{1}} = \frac{\text{Specific core loss} \times \text{Weight of core}}{V_{1}}$

$I_{C} = \frac{\text{Specific core loss} \times (K_{i} \times A_{g} \times \text{length} \times \text{density})}{V_{1}} = \frac{0.5 \times 0.9 \times 100 \times 10^{-4} \times 200 \times 10^{-2} \times 7.5 \times 10^{3}}{400}$

$\Rightarrow I_{C}=0.168 \text{ A}$

Find $I_{m}$:
We know $V1=4.44fA_{m}N_{1}$

$400 = 4.44 \times 50 \times 0.9 \times 100 \times 10^{-4} \times 0.7 \times N_{1} \Rightarrow N_{1}=286$

Magnetizing component $I_{m} = \frac{\text{Total MMF}}{\sqrt{2} N_{1}} = \frac{\text{MMF for core} + \text{MMF for airgap of length of 0.1mm}}{\sqrt{2} N_{1}}$

$I_{m} = \frac{\text{MMF for core} + B_{m} \times \frac{1}{\mu_{0}} \cdot l_{g}}{\sqrt{2} N_{1}} = \frac{2.2 \times 200 \times 0.7 \times \frac{1}{4\pi \times 10^{-7}} \times 0.1 \times 10^{-3}}{\sqrt{2} \times 286}$

$\Rightarrow I_{m}=1.226 \text{ A}$

So No load current

$I_{0} = \sqrt{I_{c}^2 + I_{m}^2} = \sqrt{0.168^2 + 1.226^2}$

$\Rightarrow I_{0}=1.237 \text{ A}$

Example 3: Design an adequate cooling arrangement for a 250 KVA, 6600/400 V, 50 Hz, 3-phase, delta/star core type oil immersed natural cooled transformer with the following particulars:
Winding temperature rise not to exceed $50^0$ C,
Total losses at $90^0$ C are 5 Kw,
Tank Dimensions height x length x width = 125 x 100 x 50 (all in cm)
Oil level = 115 cm length
Sketch diagram to show the arrangement of cooling tubes.
Solution:
Dissipating surface area of plain tank after neglecting the top and bottom
$S_{i}=2(W_{t}+D_{t})H_{t}=2(50+100)125=3.75 \times 10^{4} \text{ cm}^{2}=3.75 \text{ m}^{2}$
\[ \theta = \frac{\text{Total full load losses}}{12.5 S_1} = \frac{5000}{12.5 \times 3.75} = 106.66^\circ C \]

But it is required that the temp rise is not to exceed 50\(^\circ\) C. So cooling tubes are required.

Let \( xSt = \) Surface area of all cooling tubes
\( (12.5 S_1 + 8.5 xS_t) \theta = \) Total losses

\[ xSt = 6.25 \text{ m}^2 \]

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

\[ A_t = \pi d_{\text{tube}} l_{\text{tube, mean}} = 3.14 \times 0.05 \times 1.05 = 0.1649 \text{ m}^2 \]

No of cooling tubes \[ \frac{xS_t}{A_t} = \frac{6.25}{0.1649} \approx 38 \]

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

Total tubes =2x13+2x6=38