CHITTAGONG UNIVERSITY OF ENGINEERING & TECHNOLOGY

DEPARTMENT OF ELECTRICAL & ELECTRONIC ENGINEERING

Electrical Machine Design
EEE-240

Topics: 335kVA Transformer Design

Course Teacher: Nipu Kumar Das
Associate Professor, Dept. of EEE, CUET
Mrinmoy Dey
Assistant Professor, Dept. of EEE,CUET

Date of Submission: 5-02-2023

REMARKS

Submitted by:

Name: Md Abdul Kader Nayon
Id No:1902066

Name: Mohammad Fahim Uddin

Id No:1902068

Objective:

To design a 335 kVA, 3 phase, 50 Hz, 6.6 KV/415 V, delta/star distribution transformer. Here we will take,

- Tapping $\pm 2.5\%$, $\pm 5\%$ on high voltage side.
- Cooling O N (self oil cooled);
- Temperature rise over oil 60^0C.
- Load Loss not more than 5 kW. Percentage impedance 4.5%.
- We also Calculated:

  i. Efficiency at 75 °C on full load,75% load and 50% load at unity power factor; regulation on full load at 75 °C at unity power factor and at 0.8 power factor lagging

Solution:

Preliminary Calculations:

Voltage per turn: E_t

An empirical expression which gives voltage per turn fairly accurately for transformers is

$E_t = K\sqrt{S}$

Therefore,

$E_t = 0.45\sqrt{335}$; [here, K = 0.45, S = 335]

= 8.235volts/turn,

Assuming , 9 volts/turn

Specific magnetic loading

Chosen, $B_{max} = 1.7$ Wb / m^2;

Here, material for core is chosen as cold rolled grain oriented (CRGO) steel laminations of 0.35 mm thickness; mitred core construction is used; mitered at 45^0 Cross Section of the core:

$E_t = (4.44\ B_m\ f\ A_i)$ Volts

Where, B_m = flux density in wb/m^2, taken as 1.7wb/m^2

f = 50 Hz and A_i is net

As, E_t= 9 volts/turn

Cross sectional area of the core in the m^2

$$A_i = \frac{E_t}{4.44 \times B_m \times f}$$

$$= \frac{9\times10^6}{4.44\times1.7\times50}\ \text{mm}^2$$

$$= 21197.66826\ \text{mm}^2$$

Diameter of the circumscribing circle for the core: d

Here, we have chosen seven step cores.

So, the area should be nearly circular. In the case of a 7 step core,

The core space factor, K_i= 0.88 and

Stacking factor for laminations, K_s= 0.92

If, d = diameter of the core section,

$A_i = \frac{K_i \times K_s \times \pi d^2}{4}$

Or, $21224 = \frac{0.88 \times 0.92 \times \pi d^2}{4}$

Or, $d = \sqrt{\frac{4 \times 21197.66}{0.88 \times 0.92 \times \pi}}\ mm$

Or, $d = 193.6601\ mm$

we choose it, d = 194 mm

Then area, $A_i = \frac{0.88 \times 0.92 \times \pi (194)^2}{4}\ mm^2$

$= 23931\ mm^2$

With this area, we will now check B_m .

Here,

$$E_t = 4.44\, B_m\, f\, A_i$$

$$Or, B = \frac{E_t}{4.44\, f\, A_i}$$

$$Or, B_m = \frac{8.01}{4.44 \times 50 \times 23931}\ wbm^{-2}$$

$$Or, B_m = 1.6940\ wbm^{-2}$$

Window area A_w:

We know, $S = 3.33 \times A_i A_w B_m K_w\, \delta f \times 10^{-3}$

Here,

Window space factor, $K_w = \frac{9}{30+kV} = \frac{9}{30+6.6} = 0.273$

A_w = Window area;

δ = current density taken as 2.5 A / mm^2;

S = output in kVA;

Therefore,

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

$$= \frac{335 \times 10^6 \times 10^3}{3.33 \times 23931 \times 1.6940 \times 0.273 \times 2.5 \times 50}\ mm^2$$

$$= 72658\ mm^2$$

Now, we choose,

Window width = 171mm

Then,

Height of window $= \frac{71558}{171}$ mm

= 424.9 mm (assuming, 425)

Now choosing,

The height of the window = 425+(30*2)

= 485 mm; [checking clearance to yoke, This is later taken as 450 mm]

The main dimensions of the core are therefore:

Diameter, d = 194 mm;

D = distance between the centers of the adjacent limbs

= (184 + 171 approximate) mm; [with a 7 step core, the largest width of the core with d = 194 mm is, 0.95×194 =184 mm]

= 355 mm;

Fig: 1 shows the core and yoke assembly dimensions.

Here, Height of window = 485 mm;

Total width = (2×355) + 184 = 894 mm ;

Total height = 425 + 184×2 = 855 mm;

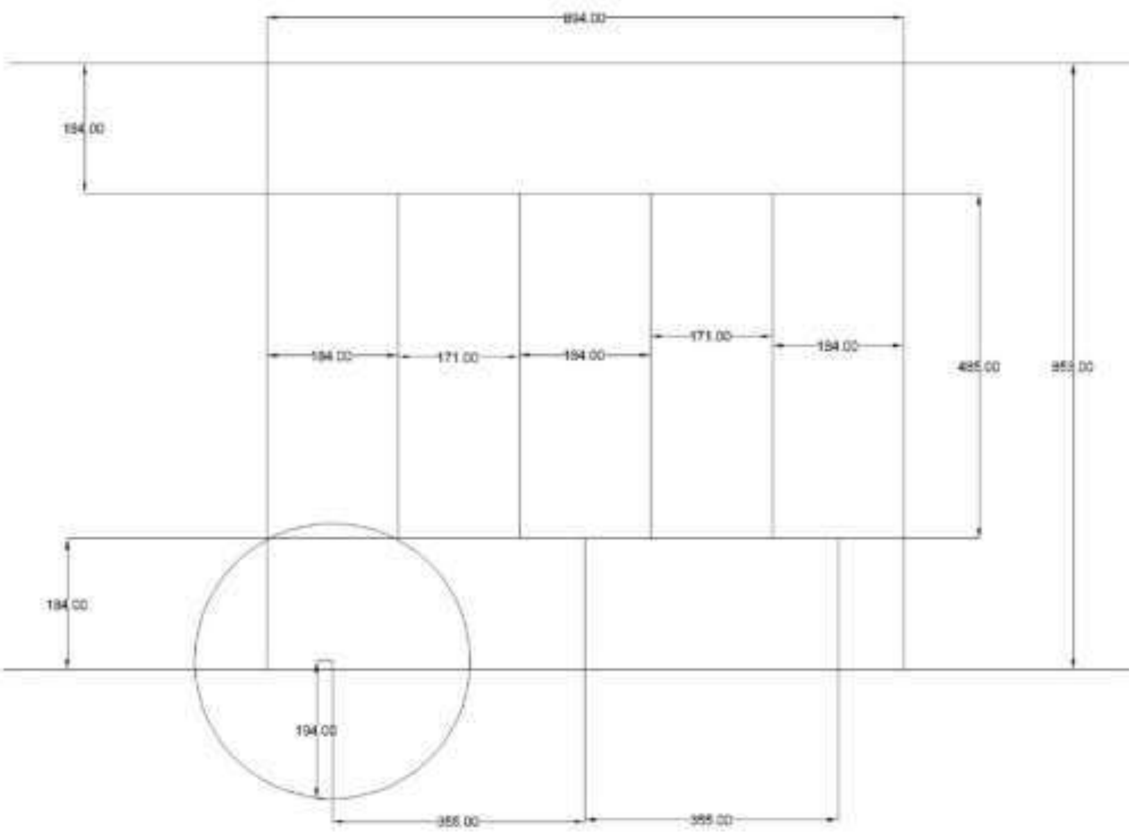

Figure 1 : Core & Assembly

Number of turn in l.v. winding:

Voltage per phase = $\frac{415}{\sqrt{3}}$ = 240 V (as the winding is star connected) ,

Turns per phase on l.v winding = 240 ÷ 9 = 26.67 , chosen as 28 turns.

Number of turns of h.v. winding:

Turns per phase on h.v. winding = $\frac{6.6\times10^{3}}{9}$ = 733.33, chosen as 735 turns

As the winding is delta connected, trappings of $\pm5\%$ and $\pm2.5\%$ are to be provided

on the h.v. winding.

Turns on h.v. winding for normal connections = 735

5% more, 1373×1.05 = 772; 2.5% more, 1373×1.025= 753

5% less, 1373×0.95 = 698; 2.5% less, 1373×0.975 = 716

Thus, **the turns for h.v. winding are:**

	5%	Normal	2.5%
more	772 turns	735 turns	753 turns
less	698 turns	735turns	716 turns

Low voltage winding

Current per phase $=\frac{335000}{415\sqrt{3}}$ A = 467 A

Here, we choose helical cylindrical coil.

Current density, $\delta = 2.5$ A / mm^2 ;

(assumed) area of l.v. conductor, $a_2 = 467 \div 2.5$ mm^2

= 186.4 mm^2

Choosing, rectangular copper conductor from IS : 1897:1962 specs.

[For rectangular copper conductors for electrical machines, giving area near about the required one.]

Now, choosing section 5 mm thickness×18.6 mm width ; 2 conductor strips Therefore, forming conductor of l.v. area, $a_2 = 18.6 \times 5 \times 2$

= 185.92 mm^2 choose 186 mm^2

High voltage winding

Here, we Choose disc coils. Now, current in h.v. winding per phase $=\frac{335000}{3\times 6600}$; (Being delta connected) = 16.92 A

Cross section of conductor for h.v. winding , $a_1 = 16.92 \div 2.5 = 6.768$ mm^{2}Choosing round conductor where, d = diameter of conductor

We know,

$$a_1 = \pi d^2 \div 4$$

Therefore, d = 2.94 mm

Now choosing, d = 2.95 mm;

we get,

Then area, $a_1 = 3.84$ mm^2

Copper area in window = $2\,(a_1T_1 + a_2T_2)$

$= 2(6.84\times 735 + 176 \times 27)$ mm^2

= 19558.8 mm^2

Now for this dimensions, we get window space factor, k_w =19558.8 ÷ 72658 = 0.269, which is near about 0.244 chosen.

Design the layout of l.v. winding :

Number of turns 27.

Size of conductor: 2 strops of 5mm × 18.6mm, copper rectangular conductors. With paper insulation for conductors, the size of each conductor will be: (5+0.25) mm × (18.6 + 0.25) mm
= 98.96 mm^2

Choosing 2 layers for l.v. winding,

Turns per layer = 27/ 2 = 14

Width of conductor 18.85 mm is taken along the winding, with 2 conductor sides 5.25 + 5.25 = 10.5 mm forming conductor per layer. For two layers, the dimension of conductors, width wise is 21 mm and height of window wise 18.85 mm for each conductor.

Height of l.v. winding in window = 12×18.85 = 226.2 mm; say 226 mm; thickness of l.v. coil = 10.5×2 = 21 mm distance between core and l.v. coil = 3.5 mm inside diameter of l.v. coil = 194 + (2×3.5) = 201 mm outside diameter of l.v. winding = 201 + (2× 21)
= 243 mm ;

Mean diameter of l.v. coil = 201 + 21 = 222 mm Mean length of turn of l.v. coil = 222π = 697.43 mm

Layout of l.v. winding is shown in Fig: 2

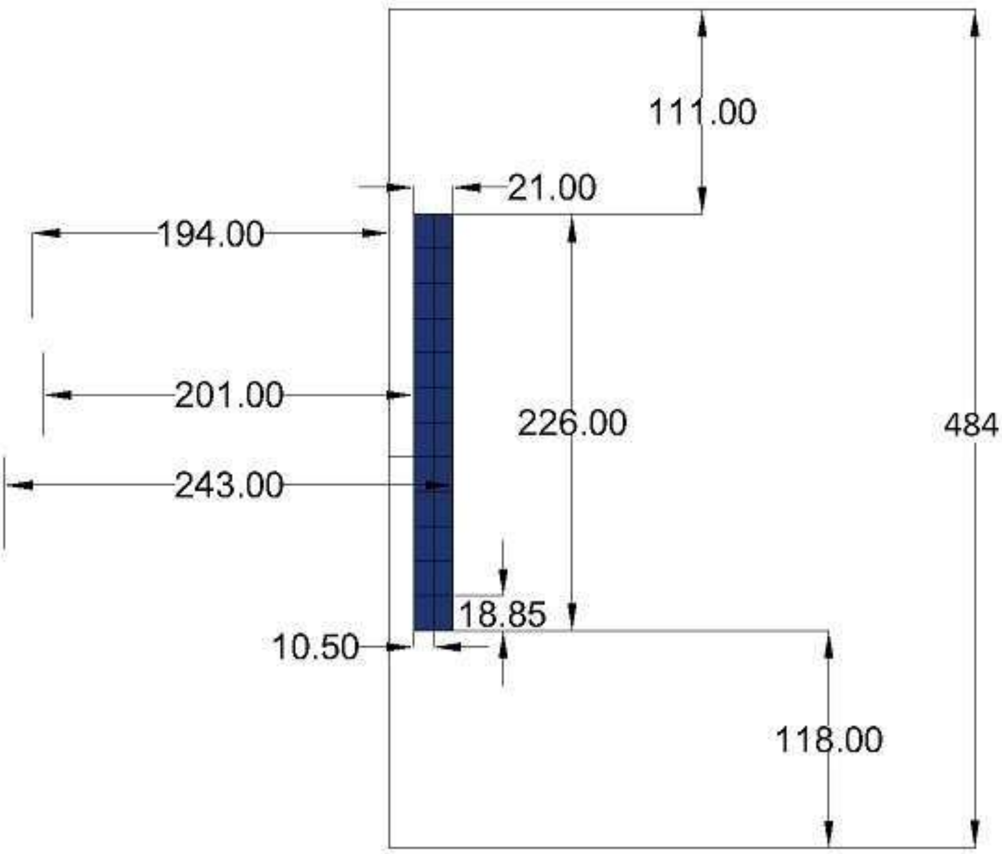

Figure 2 : Layout of l.v. winding

Design and layout of h.v. winding :

The distance between l.v. and h.v. = 12 mm

Inside diameter of h.v. = 243 + (12×2) = 267 mm

Now, Split h.v. winding in 4 coils each with turns = 772/4 = 193

The size of conductor = 2.94 mm diameter.

With paper insulation on conductor, the diameter = (2.94 + 0.25) mm= 3.19 mm

Choose 6 layers ; turns per layer = 193/6 =32.167 ≈ 32

height of winding in each h.v. coil = 32*3.2 = 102.4 mm(say, 102mm)

Thickness of each coil = 6*3.2= 19.2 mm(say, 19)

Outside diameter of h.v. coil = 267 + (2×19) = 305 mm

Approximate mean diameter of h.v. coil = 267 + 19 = 286 mm

Mean length of turn = 286 π = 898.5 mm

Height of h.v. coils in window = (102×4) +8 +8+8 =432 mm

The space required between coils and core on either side is taken as 8 mm.
The space required between coils and core on either side is taken 26 mm

The height of window required:= 432 + (26×2)= 484 mm ;
Which is acceptable

Layout of h.v. winding is shown in Fig: 3

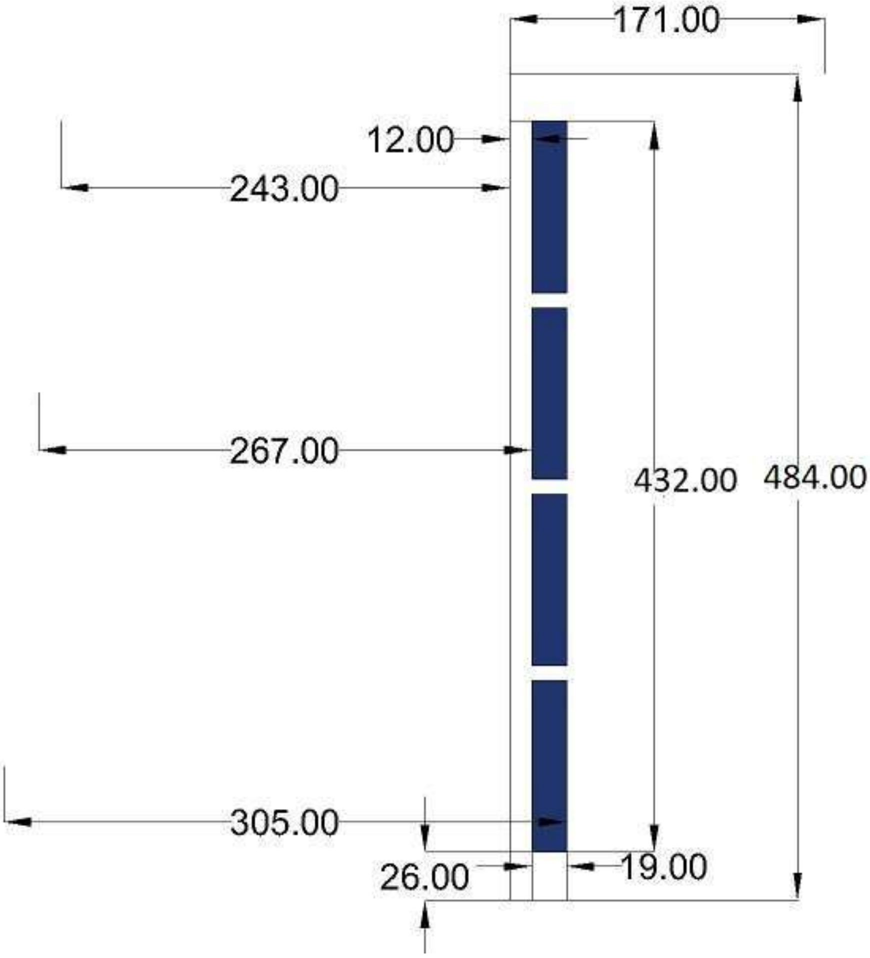

Figure 3 : Layout of h.v. winding

Percentage Reactance

l.v. mean length of turn = 697.43 mm

h.v. mean length of turn = 898= 900mm

Average L_{mt} = (698+900) ÷ 2=810
mm

AT = 467 ×27 = 12609;

Approximate mean height of coils,

h_c= (226+396) ÷ 2 = 325.2 mm

Here, a = 12mm; b_1 = width of h.v. = 19 mm; b_2 = width of l.v. = 21mm

Now,

$$a_1 + \frac{b_1 + b_2}{3} = 12 + \frac{19 + 21}{3} = 26.20\,mm$$

% reactance, X $= \frac{2\pi f \mu l_{mt}(AT)}{h_c E_t}\left(a_1 + \frac{b_1 + b_2}{3}\right)$

$$= \frac{2\pi \times 50 \times 4\pi \times 10^{-7} \times 0.820805 \times 12609}{0.3515 \times 9} \times 0.02897$$

$$= 0.036\,p.u\ or\ 3.6\ \%$$

; [its acceptable as its between 3% to 5%]

Percentage Resistance

Here,

ρ_{20} = 0.01724 ohm/mm^2/m

α_{20} =0.00393

At 75°C, $\rho_{75} = \rho_{20}\{1+ \alpha_{20}(75\text{-}20)\}$

=0.021 Ω/mm^2/m

Resistance of low voltage (l.v.) winding: (per phase) $= \frac{0.021\times\times 30}{176.4\times 1000} = 0.002091\ \Omega$

Resistance of high voltage (h.v.) winding: (per phase) $= \frac{0.021\times 900\times 772}{3.844\times 1000} = 2.15\ \Omega$

So, Ratio of transformation $= \frac{T_1}{T_2} = \frac{6600}{415} = 27.53$

Equivalent resistance referred to h.v. winding (per phase)

R = 2.15 + 0.002091×(27.53)^2

=3.74 Ω

percentage resistance, %R $= \frac{3.75}{390.71} \times 100\% = 0.9443\%$

Here,

% X = 3.6%;

% R = 0.9443%

Therefore,

Percentage impedance, $\%Z = \sqrt{3.6^2 + 0.9443^2}$

$= 3.7220\% \approx 3.8\%$

Weight of iron in core and yoke assembly:

From Fig-1, the volume of the core and yoke is given by:

$A_i \times \{(894\times2)+(485\times3)\}\ mm^3$

$=3249\times211.97$

$= 68744038\ mm^3$

Weight of iron = 7.85×1000 kg /m^3.

Weight of core and yoke $= \frac{68744038\times7.85}{1000\times1000}$kg

= 539.64 kg

Core loss at B_{max} = 1.6940 wb/m is 1.4 watts/kg

Core loss in transformer = 539.64×1.4= 755.496 watts ; (approximate)

Magnetizing volt amperes:

For B_{max} = 1.6940 wb/m^2,

VA / kg from the curve is 13 VA/kg

Magnetizing volt amperes = 539.64×13 = 7015.32VA

Weight of l.v. winding :

We know, density of copper 8.89 g/cm^3

Number of turns = 27 & a_2 = 186 mm^2

Mean length of turn = 697.43 mm

Weight of l.v. winding (per limb) $= \frac{8.89\times186\times27\times697.43}{1000\times1000}$ = 31.14 kg

Weight of h.v. winding (per limb):

Number of turns = 772; normal= 735; a_1 = 6.84 mm^2 ; Mean length of turn = 898.5 mm

Weight of 4 coils (one limb) $= \frac{8.89\times6.84\times898.5\times772}{1000\times1000}$ ~~kg~~

$= 42.179$ kg; for all turns

For normal turns,

weight of the coils (one limb) $== \frac{8.89\times 6.84\times 898.5\times 735}{1000\times 1000}$ kg

$= 40.15$ kg

Total weight of copper in transformer:

We can write,

3 (l.v. + h.v.) = 3 (26.053 +43.97) =213.17 kg(say, 213 kg)

Copper loss and load loss at 75^{0}C :

h.v. current per phase = 16.92 A

Copper loss for 3 phases = $3I^2R$

$= 3\times 16.92^2\times 3.75$

= 3220.72

wattsLet, stray load loss about 7%,

Then, load loss (at 75^{0}C) = 3220.72×1.07 watts

= 3446.17 watts

Iron loss = 755.496 watts

Therefore, total loss = (755.496+3446.17)

= 4201.67watts

Calculation of performance:

- Efficiency on full load at unity power factor :

  Output = 317000 watts.

  Efficiency $= \frac{335000}{335000+4201.67}\times 100\%$

  $= 98.76\%$

- Efficiency on 3/4th full load at unity power factor:

  Core loss = 755.496 watts;

  Load loss on 3/4 load = 4201.67×$(3/4)^2$

  = 2363.44 watts

  Total loss = (755.496+2363.44) watts

  = 3118.936 watts

Efficiency on 3/4th of full load $= \frac{335000}{335000+3118.936}\times 100\%$

$= 99.07\%$

Efficiency on ½ of full load at unity power factor:

Core loss = 755.496watts;

Load loss on 1/2 load = $4201.67\times(1/2)^2$

= 1050.42watt

Total loss = (1050.42+755.496) watts

= 1805.913 watts

Efficiency on 1/2 of full load$=\frac{335000}{335000+1805.91}\times 100\%$

$= 99.46\%$

Regulation on full load at unity power factor:

% R = 0.9443%,

% X = 3.6%

Now,

$(V + IR)^2 + (IX)^2 = E^2$

Or, $(1.0 + .009443)^2 + (.036)^2 = E^2$

Or, E = 1.01

Regulation = 1.01– 1.0

= 0.01 p.u.

= 1%

Regulation on full load at 0.8 power factor lagging

= [IR cos φ + IX sin φ] %

= [0.9443×0.8 + 3.6×0.6] %

= 2.19%

Core loss current, magnetizing current, no load current :

Core loss = 755.496 watts.

core loss current, $I_c = \frac{755.496}{3\times6600}$ A

=0.0381 A

Magnetizing VA = 7015.32 ;

Magnetizing current, $I_m = \frac{7015.32}{3\times6600}$ A

= 0.354 A

No load current per phase , $I_o = \sqrt{0.354^2 + 0.0381^2}$ A

= 0.356 A

Current per phase = 16.92 A

No load current $= \frac{0.356}{16.92} \times 100\%$

= 2.104% ; of full load current

Design of tank:

Fig: 4 show the spacing of outside diameters of h.v. coils on the cores.

Outside diameter of h.v. = 305 mm

The distance between coils on adjacent limbs = 50 mm;

Clearance at each end is 52 mm.

Thus, the length of the tank = 305×3 + 50×2 + 2×52 = 1120mm

Breadth of the tank = 305 + 60×2 mm

= 425 mm ;

Choose 430 mm

Height = 855 + 50 mm for base + 210 oil level above core +250mm for leads;

= 1115 mm up to oil level +250mm for leads;
=1365 mm

Inside dimensions of the tank of the transformer

= (length×breadth×height)

= (1365×430×1120) mm^3

= 657384000 mm^3

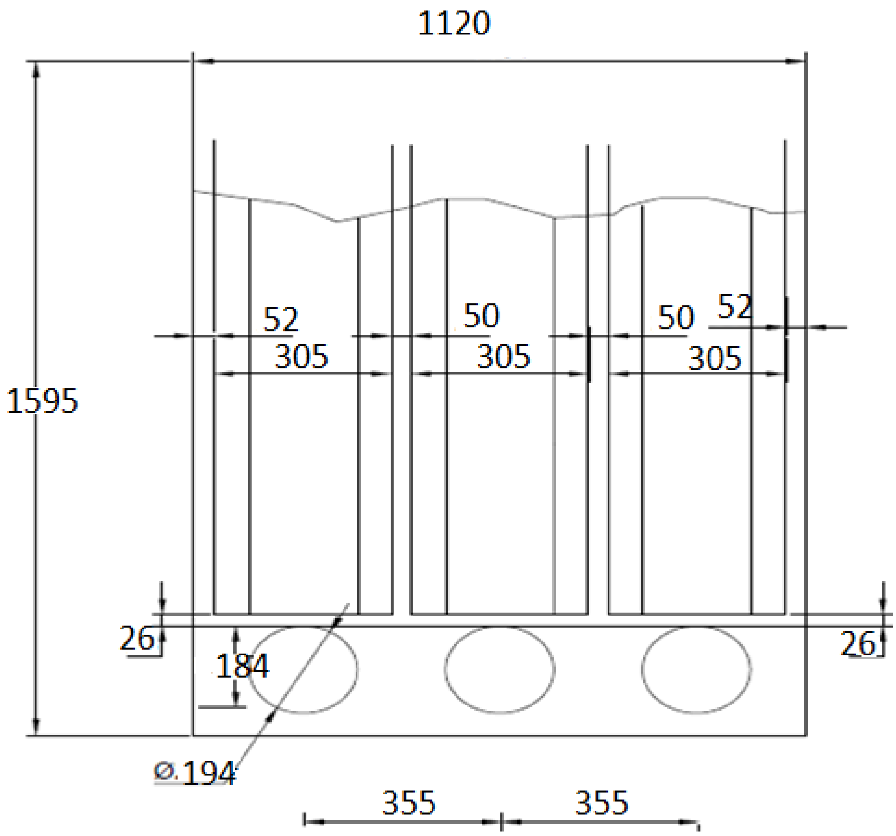

Figure 4: Tank Dimensions

Temperature rise:

Now, for dissipation of heat only 4 surfaces of a tank are taken into consideration.

The top and the bottom are not considered.

Surface of tank $= \frac{1365}{1000} \times \frac{430}{1000} \times 2 = 1.1739\ m^2$

$= \frac{1365}{1000} \times \frac{1120}{1000} \times 2 = \underline{3.0576\ m^2}$

Total $= (1.1739+3.0576)\ m^2 \quad = 4.2315\ m^2$

Full load loss to be dissipated = 4201.67 watts

Now, If 16.5 watts per m^2 per ^{0}C temperature rise is taken as dissipation due to convention and radiation,

The temperature rise $= \frac{4201.67}{16.5 \times 423151} = 59^0$C

Now, to maintain the temperature of transformer walls limited to

35^0C, Then temperature rise of the oil will be 50 ^{c} C and of coils 55

^{0}C. In that case the surface of the tank for cooling has to be increased

either by "radiators" or "tubes" attached to the tank.

If the total surface area is considered, '$\boldsymbol{x}$' times the tank surface area, we get:

$$4.23x\left(8.88 + \frac{3.7}{x}\right) 35 = 4201.67$$

from which, $\boldsymbol{x} = 2.73$

Thus,

Additional area to be provided = 3.07 x 0.88 = 2.7 m^2

As, 1115 mm is height up to oil level;

Height of tube is taken as 1000 mm

Surface of 1 tube of 50 mm diameter = π x 50 x 1000 x $l0^{-6}$

= 0.1571 m^2

Number of tubes required = 2.7/0.1571

= 17 ; approximately

Volume & weight of oil:

Volume of tank to oil level of 1365 mm $= \frac{1365}{1000} \times \frac{495}{1000} \times \frac{1365}{1000} m^3 = 0.854\ m^3$

Volume of transformer core and copper:

$$\frac{213.17}{7.85 \times 1000} + \frac{539.64}{7.85 \times 1000}\ m^3$$

= 0.0958 m^3

Volume of oil required= (0.89-0.0958) m^3 = 0..794 m^3

Oil required in transformer = 0.794×1000 liters

= 794 liters .

Therefore, weight of oil required = (794× 0.89) kg

= 706.66 kg

Weight of tank:

If the thickness of the tank walls is taken as 5 mm.,

Weight of tank $= 0.005 \left(\frac{1365}{1000} \times \frac{430}{1000} \times 2 + \frac{1258}{1000} \times \frac{1120}{1000} \times 2 + \frac{1120}{1000} \times \frac{430}{1000} \times 2\right) \times 1000 \times 7.85$ kg

= 203.89 kg

Volume and weight of oil in tube:s

Here,

17 tube each of 50 mm diameter and 1 m length.

Therefore, Volume $= \frac{\pi}{4} \times (\frac{50}{1000})^2 1 \times 17$

= 0.03338 m^3,

Volume of oil in tubes = 0.03338×1000 = 33.38 liters.

Weight of oil in tubes = 33.38 x 0.89 kg = 29.70 kg

Weight of tube $= \pi Dl \times 0.005 \times 14 \times 7.85 \times 1000$ kg

$= \pi \times \frac{50}{1000} \times 1 \times 0.005 \times 17 \times 7.85 \times 1000$ kg

= 104.43 kg

Total weight of transforme:r

Weight of core and yoke assembly	539.64 kg
Weight of copper in windings	213.17 kg
Weight of tank	203.89 kg
Weight of tubes	104.43 kg
Weight of oil in tank and tubes	678 kg
Weight of oil in tubes	47.17kg

Total weight= 1761.13 kg

Summary

Transformer designed as per IS : 1897:1962
Specifications

kVA 335 ; Volts H.V. 6600 volts; Volts L.V. (no load) 415 volts; Amperes H.V. 16.92A ; L.V. 417 A (line values); 3 phase, delta/star 50 c/s; temperature rise of oil 59^0C ; type of cooling O N ; Vector group; percentage impedance 3.8%

±2.5% and ±5% tappings on h.v. side.

Core and yoke

Material : CRGO (cold rolled grain oriented) steel laminations 0.35 mm thick; mitred core construction 45° cut.

Flux density B_{max}=*1.69* Wb/m^2; Net area of cross section of core, 23931 mm^2; circumscribing circle diameter 185 mm.

Size of core, yoke and frame: width of the window, 894 mm; height of window,425 mm;

Weight of core and yoke assembly 539.64 kg; core loss at B_{max} = 1.69 wb / m^2, 1.4 watts per kg ; magnetizing VA = 13 VA / kg

Windings	**L.V**	**H.V**
Type of winding	Helical	Disc
Current density	2.5 A/mm^2	2.5 A/mm^2
Cross sectional area of conductor	186 mm^2	6.84 mm^2
Conductor : Copper	2 strips of 18.6mm×5mm	diameter 2.94mm
Number Of Layers per limb	2	6 discs
Number of turns	27	735 normal 772 max tapping
Number of turns per layer	14	32
Height of winding in window	226 mm	396 mm

Thickness of coil	21 mm	19 mm
Inside diam of coil	201 mm	267 mm
Outside diam of coil	243 mm	305 mm
Mean length of turn	697.43 mm	898.5 mm
Resistance at 75^0c	0.00189 ohms	2.15 ohms
Weight of copper for winding per limp	31.14 kg	42.178 kg
Total Weight Of Copper	31.14 kg	188 kg kg

Insulation

Insulation between core and l.v. winding : pressboard paper

Insulation for conductors : paper

Insulation between layers : Crape paper

Insulation between l.v. and h.v. windings : bakelized paper cylinder; Laminated pressed wood sticks for spacers for cooling.

Class A insulation for O N type transformers.

Tank : Temperature rise of oil 59^0C

Inside dimensions of tank : length 1365 mm; breadth :430 mm; height 1120 mmTubes,

17each of 50 mm diam; 1000 mm long

Oil in transformer tank	761.8 liters
Oil in tubes	33.8 liters
Weight of oil in tank	678 kg
In tubes	30.082 kg
Weight of tank	203.89 kg
Of tubes	104.43 kg

weight of complete transformer	1761.13 kg
Performance :	
Percentage resistance	0.9443%
Percentage reactance	3.6%
Percentage impedance	3.8%
Iron loss	755.496 watts
Copper and stray load loss, i.e. load loss at 75^0C	3446.17 watts
Total loss on full load	4201.67 watts
Efficiency on full load at unity power factor	98.76%
Efficiency on 3/4 th full load at unity power factor	99.07%
Efficiency on 1/2 full load at unity power factor	99.46%
Regulation on full load at unity power factor	1%
Regulation on full load at 0.8 power factor lagging	2.91%
Core loss current per phase	0.0381A
Magnetizing current per phase	0.354A
No load current per phase	0.356A

Tappings

772	753	735	716	698
5%	2.5%	normal	-2.5%	-5%