Chittagong University of Engineering And Technology

Department of Electrical And Electronic Engineering

Project Topic: Design of a Distribution Transformer

Course No : **EEE-240**

Course Title : **Electrical Machine Design**

Submitted to : **Mrinmoy Dey**

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Level : **2**

Term : **II**

Section : **B**

Group : **15**

REMARKS

❖ Objective:

To design a 412 kVA, 3 phase, 50 Hz, 11 KV/415 V distribution transformer.

Given Parameters:

- Tapping ±2.5%, ±5% on high voltage side.
- LV is in Wye connection and HV is in Delta connction.
- Cooling ON (self oil cooled);
- Temperature rise over oil 50^0C.
- No load loss not more than 7 KW; Percentage impedance 4.5%.

Need to Calculate:

- No load current.
- Efficiency at 75^0C on full load,75% and 50% load at unity power factor.
- Regulation on full load at 75^0C at unity power factor and at 0.8 power factor lagging.

❖ Voltage per Turn

Let, voltage per turn= E_t

We know, $E_t = \frac{\sqrt{\frac{KVA \times 1000}{no.\ of\ legs}}}{40}$

Therefore, $E_t = \frac{\sqrt{\frac{412 \times 1000}{3}}}{40}$ volts/turn [no of legs of three phase core type transformer is 3]

❖ Chosen Magnetic Specification

Here, material for core is chosen as cold rolled grain oriented (CRGO) steel laminations of 0.35 mm thickness.

Specific magnetic loading, B_{max}= 1.7 T

❖ Cross Section of the Core

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

Where, B_m= Flux density in wb/m^2 =1.7 wb/m^2

f = 50 Hz

E_t= 9.3 Volts/turn

Cross sectional area of the core, $A_i = \frac{Et}{4.44 \times f \times Bm}$

$= 0.024642\ m^2 = 24642\ mm^2$.

❖ Determining diameter of core

We have chosen seven step cores to make the core nearly circular.

In the case of a 7-step core, the core space factor, K_i= 0.88

Stacking factor for laminations, K_s= 0.92

If d = diameter of the cross section,

$A_i = (0.88) \times (0.92) \times (\pi d^2/4)$

Therefore, $d = \frac{4 \times A_i}{0.88 \times 0.92 \times \pi} = \frac{4 \times 24642}{0.88 \times 0.92 \times \pi} = 196.86$ mm

Choosing d= 200 mm.

Then area, $A_i = 0.88 \times 0.92 \times \pi \times (200)^2/4\ \ mm^2$

$= 25434.33 \approx 25434\ mm^2$

Now, with this area, we will now check B_m.

❖ Window Area Calculation

We know,

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

$\therefore A_w = \frac{S}{3.33 \times 25434 \times 0.24 \times 2.5 \times 1.65 \times 10^{-6} \times 50 \times 10^{-3}}$

$= 98272.75 \approx 98273\ mm^2$

Window space factor (k_w) is taken approximately as 0.24

A_w = Window area;

$B_m = 1.65 wb/m^2 = 1.65 \times 10^{-6} wb/mm^2$

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

S = output in kVA = 412kVA

❖ Core & Window Dimension

Choosing window width =210mm

Height of window = 98273/210

=467.97 ≈468mm

Now we consider the height of the window= 500 mm

∴Window area= 500×210 mm^2 =1050000 mm^2

<u>The main dimensions of the core</u>

Diameter, d =200 mm;

D = distance between the centers of the adjacent limbs

= 200×0.95+210mm =400mm

Height of window = 500 mm;

∴ Total width = (400×2)+(200×0.95) =990mm

∴ Total Height=500+(200×0.95)+(200×0.95) =880mm

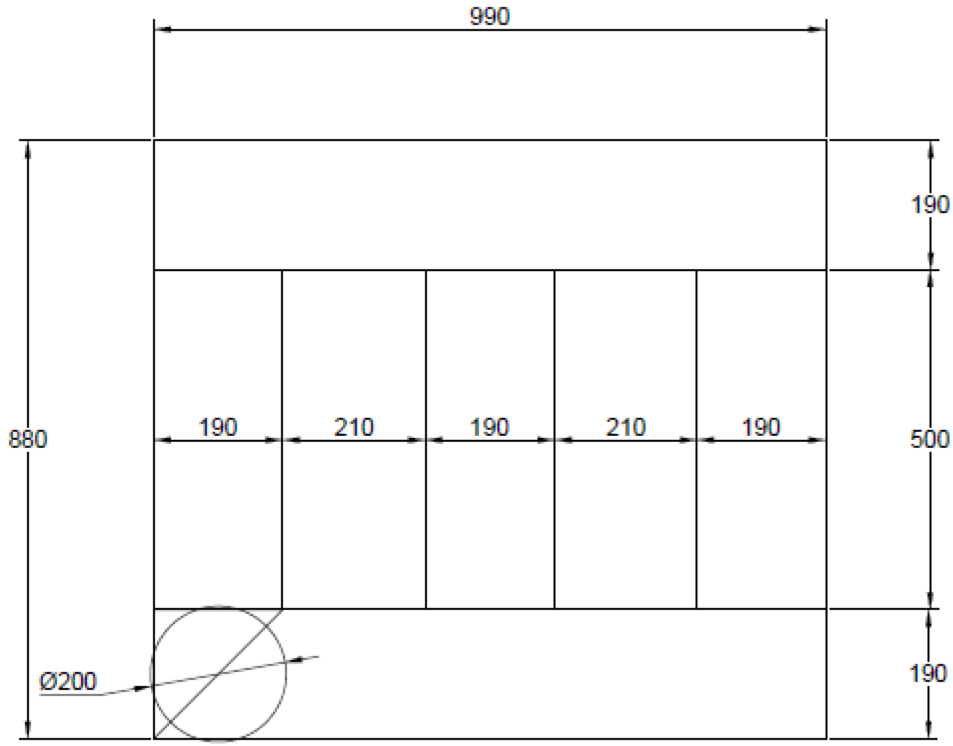


Fig. 01: Schematic of Core & Assembly

❖ Number of turns in LV (Y-connected)

Voltage per phase = 415/√3 = 239.6 V

Turns per phase on LV winding =239.6/9.3 =25.76 ≈ 26turns.

❖ Number of turns in HV (Δ-connected)

Voltage per phase = 11k V

Turns per phase on HV winding =11×10^3/9.3 =1182.795 ≈ 1183turns.

As the winding of HV is delta connected,

Tapping of ± 5% and ± 2.5% are to be provided.

Tapping	5%	Normal	2.5%
More	1183+1183×.05=1243	1183	1183+1183×.025=1213
Less	1183 -1183×.05=1124		1183 -1183×.025=1254

❖ Low Voltage Winding

Current per phase = $\frac{(412\times10^3)}{\sqrt{3}*415}$ =139 A.

Here, we chose helical cylindrical coil.

Current density, δ = 2.5 A/mm^2 (assumed).

Area of L.V. conductor, a_2 = 573/2.5 = 229.2 mm^2 ≈ 230 mm^2.

Choosing, rectangular copper conductor from IS: 6160: 1977 specs,

Let, Cross Section = T × W.

Taking them in a ratio of 1.42:1,

Cross Section = 9 mm × 12.8 mm.

Since there is 2 conductor strips, L.V. area, a_2 = 9×12.8×2 mm^2 = 230.4 mm^2 = 230 mm^2.

❖ High Voltage Winding

Current in H.V. winding per phase = $\frac{(103\times 412)}{3\times 11\times 103}$ = 12.48 A.

Cross section of conductor for H.V. winding, a_1 = 12.48/2.5

= 4.992 mm^2.

Choosing disc coil and round conductor where, d = diameter of conductor.

Now, $a_1 = \pi d^2/4$

or, $d^2 = 6.356 \quad \therefore d = 2.52$ mm.

Copper area in window = $2(a_1T_1 + a_2T_2) = 2(4.992\times1243 + 230\times26)\ mm^2$

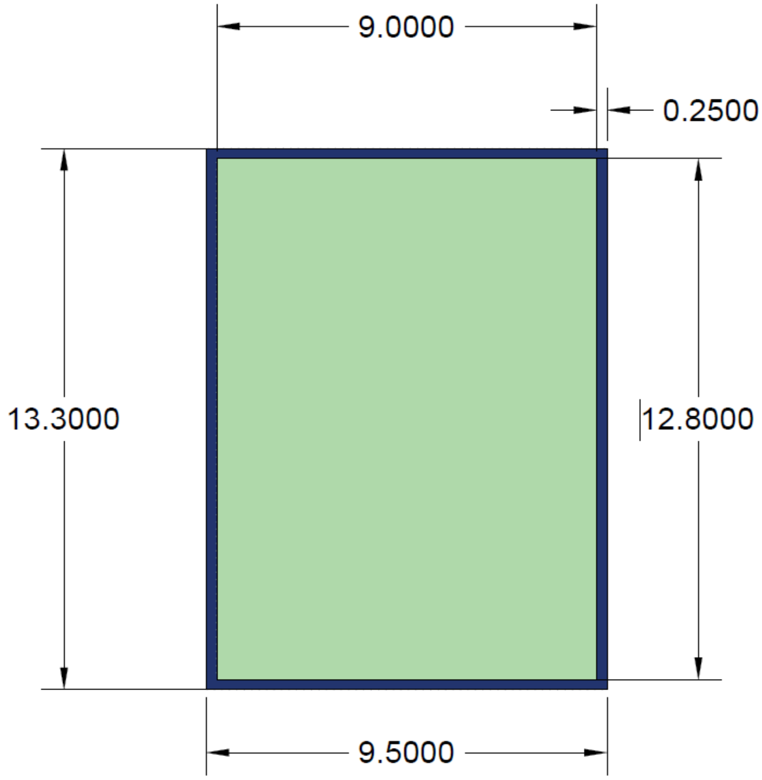
= 24370.112 mm^2.

Now for this dimensions, we get window space factor, k_w = 24370.112/98486

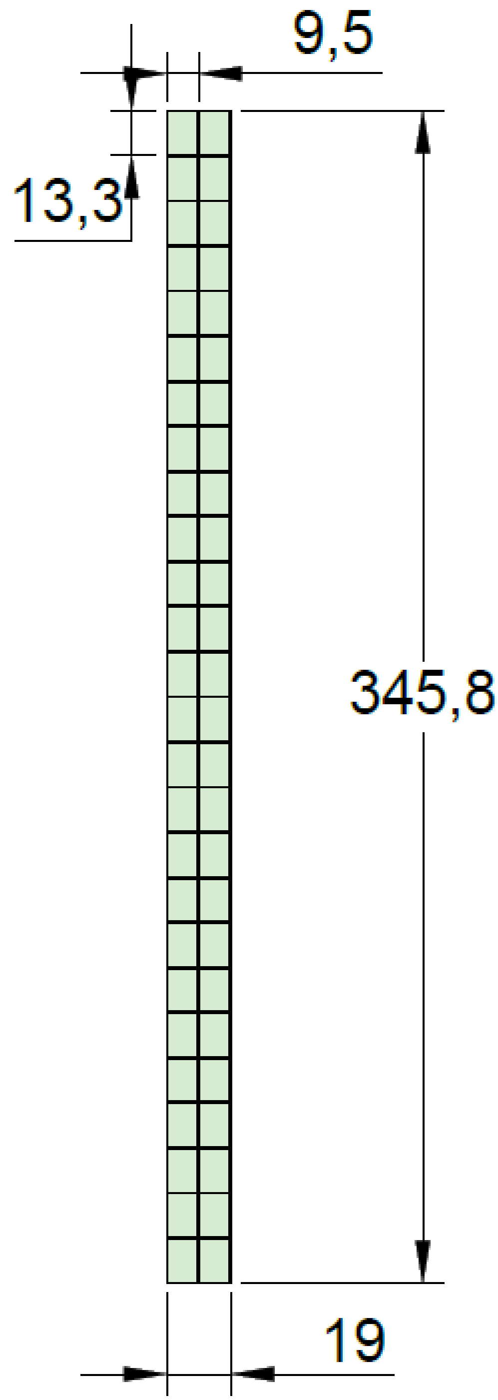
= 0.247 ≈0.25 (chosen)

❖ Design and Layout of LV Winding

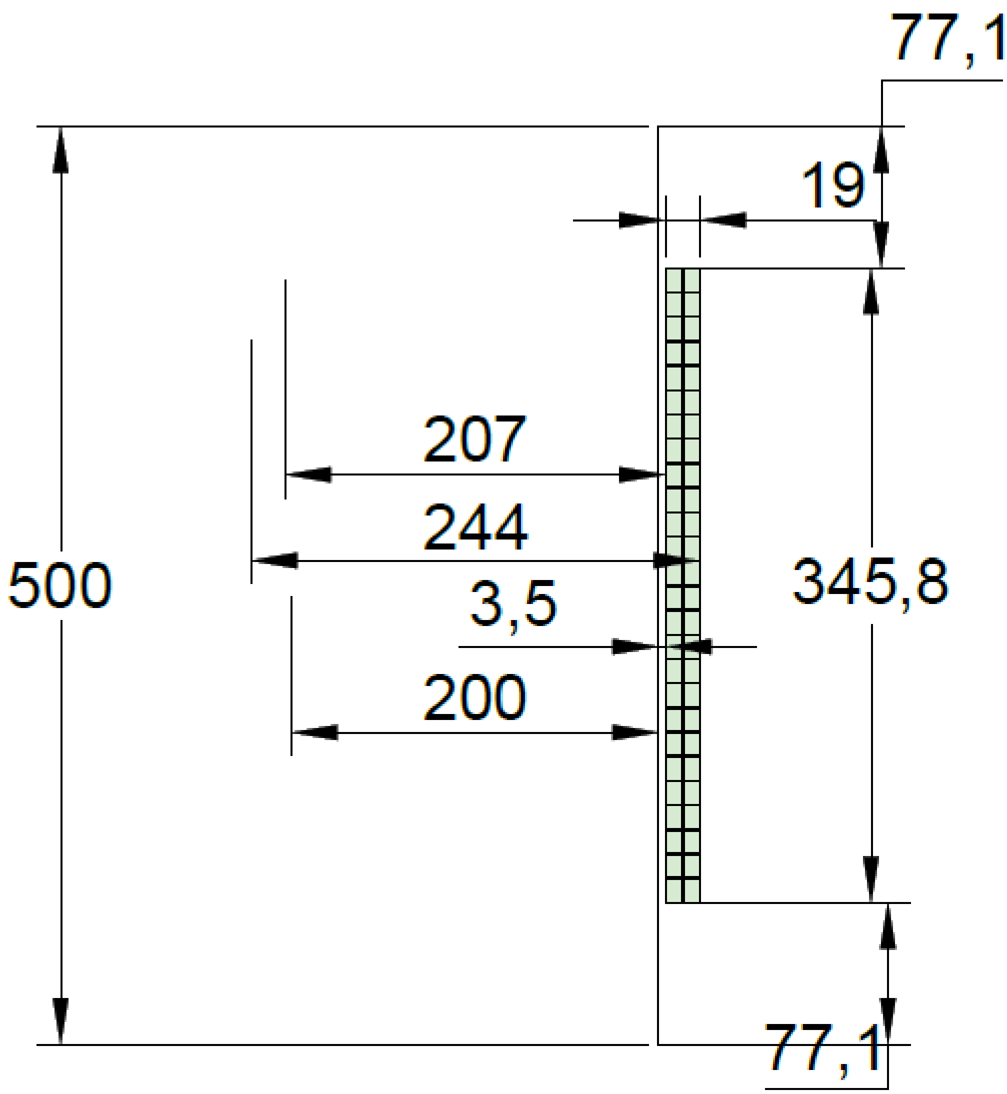
- Number of turns in L.V= 26.
- Size of conductor = 2 strips of 9×12.8.
- We consider paper insulation of conductor is = 0.25 mm.
- With paper insulation, 2 strips of conductor = (9+ 0.25) mm × (12.8 + 0.25) mm.
- Choosing **1 layer** for L.V. winding, turns per layer = 26.
- Width of conductor 13.05 mm is taken along the window with 2 conductor sides 9.25 + 9.25 = 18.5 mm forming conductor per layer.
- For 1 layer, the dimension of conductors width wise = 18.5 mm.
- Height of L.V winding in window= 26×13.05= 339.3mm ≈340mm (chosen)
- Thickness of L.V coil = 18.5 mm.
- Distance between core and L.V coil = 3.5 mm.
- Inside diameter of L.V coil = 200+(2 × 3.5) = 207 mm.
- Outside diameter of L.V. winding = 207 + (2 × 18.5) = 244mm.
- Mean diameter of L.V. coil = 207 + 18.5= 225.5 mm.
- Mean length of turn of L.V. coil = π×d= 225.5× π = 708.43 mm.



(a) Dimension of single conductor in the layer



(b) Dimension of LV coils in 1 layer



(c) Overall Layout of LV coil

Fig. 02: Design and Layout of LV Winding

❖ Design and Layout of HV Winding

- The distance between LV and HV = 12 mm.
- Inside diameter of H.V. =244 + (12× 2) = 268mm.
- Split H.V. winding in 4 coils each with turns = 1243/4 = 310.75 ≈311(chosen).
- The size of conductor = 2.52 mm.
- With paper insulation on conductor, the diameter = (2.52 + 0.25) mm = 2.77 mm.
- Choosing **9 layers**, Turns per layer = 311/9 =34.56 ≅ 35.
- Height of winding in each H.V. coil = 35× 2.77 = 96.95 ≈97 mm.
- Thickness of each coil = 9 × 2.77 = 24.93 mm.
- Outside diameter of H.V. coil = 268 + (2×24.93) = 317.86 mm.
- Mean diameter of H.V. coil = 268 + 24.93 = 292.93 mm.
- Mean length of turn = π×d= 292.93× π =920.27 mm.
- Height of H.V. coils in window = (97× 4) +8+8+8 = 412 mm.
- The space required between coils and core on either side is taken as 44 mm.
- The height of window required = 412 + 44× 2 = 500 mm.

❖ Percentage Reactance

- LV mean length of turn= 225.5× π = 708.43 mm.
- HV mean length of turn = 292.93× π =920.27 mm.
- Average, Lmt = $\frac{708.43+920.27}{2}$ =814.35 mm
- AT = L.V Amp ×L.V. turn =573× 26 = 14898.
- Mean height of coils, h_c = (412+340)/ 2 = 376 mm.
- a +$\frac{b1 + b2}{3}$ =12 + $\frac{24.93 + 18.5}{3}$

  = 26.48 mm.

Here,

a = 12 mm;

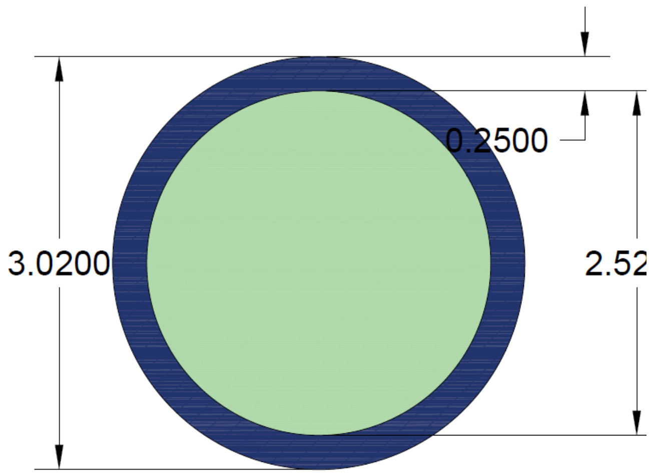
b1 = width of HV = 24.93mm

b2 = width of LV =18.5 mm

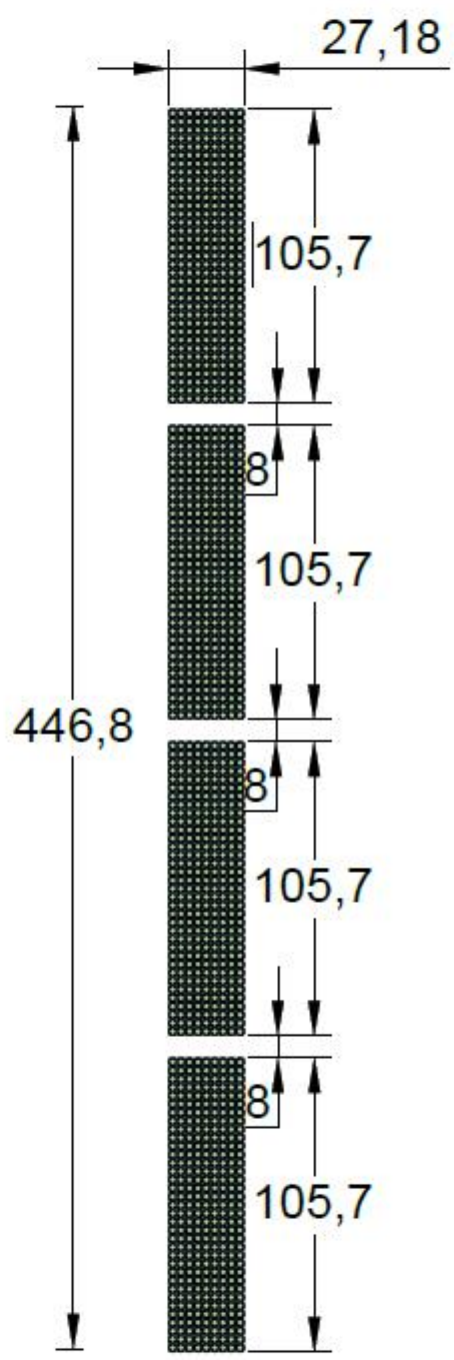
Therefore, % X = $\frac{2\pi f \mu_0 L_{mt}(AT)}{h_c E_t} \times (a + \frac{b_1+b_2}{3})$

$= \frac{2\pi \times 50 \times 4\pi \times 10{-}7 \times 0.81435 \times 14898 \times 0.02648}{0.376 \times 9.3}$

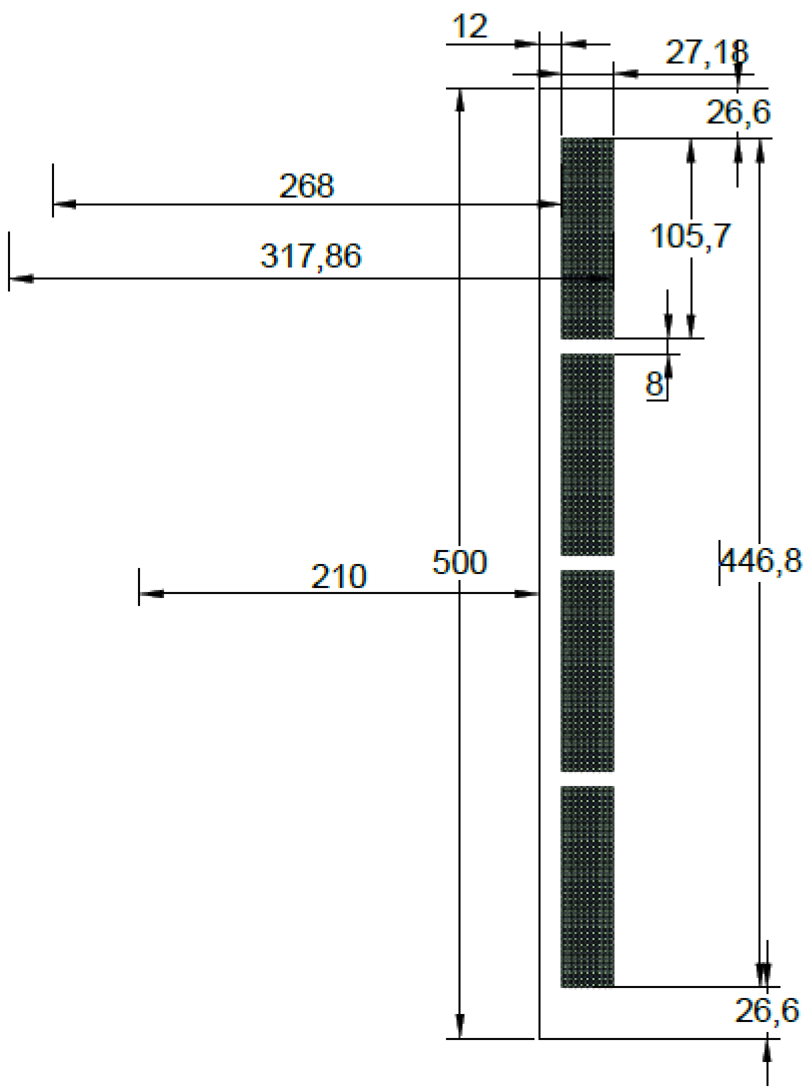
= 0.03627 p.u. =3.63%.



(a) Dimension of single conductor in the layer



(b) Dimension of HV coil with 9 layers



(c) Overall layout of HV coil

Fig. 03: Design and Layout of HV Winding

❖ Percentage Resistance

We Know, ρ_{20} = 0.01724 Ω/mm^2 /m and α_{20} =0.00393

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

$= 0.01724(1+0.00393\times55) \quad =0.021\ \Omega/\ mm^2/m$

- Resistance of low voltage (L.V.) winding (per phase),[R=ρL/A]

$$R = \frac{0.021 \times 708.43 \times 26)}{230 \times 1000}\ \Omega$$

$= 0.00168\ \Omega$ (per phase).

- Resistance of high voltage (H.V.) winding (per phase), [R=ρL/A]

$$R = \frac{0.021 \times 920.27 \times 1243)}{4.992 \times 1000}\ \Omega$$

$= 4.81\Omega$ (per phase).

Now, Ratio of transformation = $(11\times10^3)/ 239 = 46$

Resistance of L.V. winding = 0.00168 Ω (per phase)

Resistance of H.V. winding =4.81Ω (per phase).

Now,

Equivalent resistance referred to H.V. winding (per phase),

$$R_{eq} = 4.81+ 0.00168 \times (46)^2\ \Omega = 8.36\ \Omega.$$

Therefore,

Percentage resistance, % R = (Eq. Resistance / Base Resistance)

Therefore, $\%R = \frac{8.36}{11\times 103\ /12.48} \times 100\% = 0.00948$ p.u

$=0.948\%$.

❖ Percentage Impedance

Finally, % X = 3.63%.

% R = 0.948%.

∴Percentage impedance, $\%Z = \sqrt{(3.63^2 + 0.948^2)}$

$= 3.75\ \%$

which is acceptable as the acceptable limit is (3.5-4.5)%.

❖ Weight of Iron in Core and Yoke Assembly

- The volume of the core and yoke is given by= $A_i \times \{ (990 \times 2) + (500 \times 3) \}\ mm^3$

  $= 25434 \times 3480\ mm^3$

- Weight of iron = $7.85 \times 1000\ kg/m^3$.
- Weight of core and yoke = $(25434 \times 3480 \times 7.85) \div (1000 \times 1000)$

  $= 694.8\ kg$
- Core loss at $B_{max} = 1.65\ wb/m^2$ is 1.3 watts/kg (From fig.06)
- Core loss in transformer = $694.8 \times 1.3 = 903.24$ watts (approximately)

❖ Magnetizing Volt-Amperes

- For $B_{max} = 1.65\ wb/m^2$,

  VA/kg from the curve is 10 VA/kg (From fig.06)

- Magnetizing volt amperes = $694.8 \times 10 = 6948$ VA

❖ Weight of LV Winding

- We know, density of copper= 8.89 g/cm^3
- Number of turns=26 & a_2=230 mm^2
- Mean length of turn=708.43 mm
- Weight of L.V. winding (per limb) = $\frac{8.89\times230\times708.43\times26}{1000\times1000}$ =37.66kg

❖ Weight of HV Winding

- Number of turns = 1243; normal = 1183;
- a1 = 4.992 mm^2;
- Mean length of turn = 920.27 mm.
- Weight of 4 coils (one limb) = $\frac{8.89\times4.992\times920.27\times1243}{1000\times1000}$ kg

  = 50.76 kg (for all turns)
- For normal turns,

  Weight of the coils (one limb) = $\frac{8.89\times4.992\times920.27\times1183}{1000\times1000}$ kg

  = 48.31kg.

❖ Total Weight of Copper(Cu) in Transformer

3(Weight$_{LV}$ + Weight$_{HV}$) = 3(50.76+48.31) kg

=297.21kg

❖ Copper Loss and Load Loss at 75°C

- H.V. current per phase = 12.48 A
- Copper loss for 3 phases = $3 \times I^2 \times r$

  $= 3 \times 12.48^2 \times 8.36 = 3906.2$Watts

  Let, stray loss be about 7%.
- load loss (at 75^0C) = 3906.2×1.07= 4179.634Watts
- Iron loss = 903.24 watts Therefore,
- Total loss = (903.24+4179.634)

  = 5082.874 watts.

❖ Calculation of Performance

- **Efficiency on full load** at unity power factor:

  Output = 412×1000×1 watts.

  Efficiency = $((412 \times 1000)/(412 \times 1000 + 5082.874)) \times 100\%$

  = 98.78%
- **Efficiency on 3/4th full load** at unity power factor:

  Core loss = 903.24 watts;

  Load loss on 3/4 load = $5082.874 \times (3/4)^2 = 2859.12$ W

  Total loss = 903.24 + 2859.12W = 3762.36 watts

  Efficiency on 3/4th of full load $= \frac{3/4 \times 412 \times 1000}{3/4 \times 412 \times 1000 + 3762.36} \times 100\%$ = 98.99%
- **Efficiency on ½ of full load** at unity power factor:

  Core loss = 903.24 watts;

  Load loss on 1/2 load = $5082.874 \times (1/2)^2 = 1270.72$W

  Total loss = (903.24 + 1270.72)

  = 2173.96 watts.

  Efficiency on 1/2 of full load $= \frac{1/2 \times 412 \times 1000}{1/2 \times 412 \times 1000 + 2173.96} \times 100\%$ = 98.96%

❖ Regulation on Full Load at Unity Power Factor

% R = 0.948% ; % X = 3.63%

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

or, $(1+0.00948)^2+(0.00363)^2= E^2$

or, $E^2=1.019$

or, $E =1.009$

Regulation=1.009-1=0.009p.u. =0.9%

❖ Regulation on Full Load at 0.8 Power Factor Lagging

[IR cos φ + IX sin φ] %

=[0.948×0.8+3.63×0.6]% = 2.94%

❖ Core Loss Current, Magnetizing Current, No-load Current

- Core loss = 903.24 Watts.
- core loss current, Ic = $\frac{903.24}{3\times11000}$A

  = 0.027 A
- Magnetizing VA = 6948;
- Magnetizing current, Im =$\frac{6948}{3\times11000}$ = 0.2105 A
- No load current per phase , Io = $\sqrt{(0.027^2 + 0.2105^2)}$

  = 0.212 A
- Current per phase = 12.48 A
- No load current = $\frac{0.212}{12.48}\times 100$ %

  =1.699% of full load current

❖ Design of Tank:

From HV coil on the core,

- The distance between coils on adjacent limbs=82.14mm

[400-317.86(outside diameter of HV=82.14]

- Outside diameter of HV=mm
- Clearance at each end=44.5mm (Assumed)

Length of the tank = 317.86×3+82.14×2+44.5×2 =1206.86mm ≈1207mm

Breadth of the tank= 317.86+60×2mm =437.86 ≈438
Height of the tank = 880+50mm for base+250 for oil level above core

=1180mm+250 for leads etc. =1430mm

Inside dimension of the tank of the transformer=1207×438×1430 (Length×Breadth×Height)

v

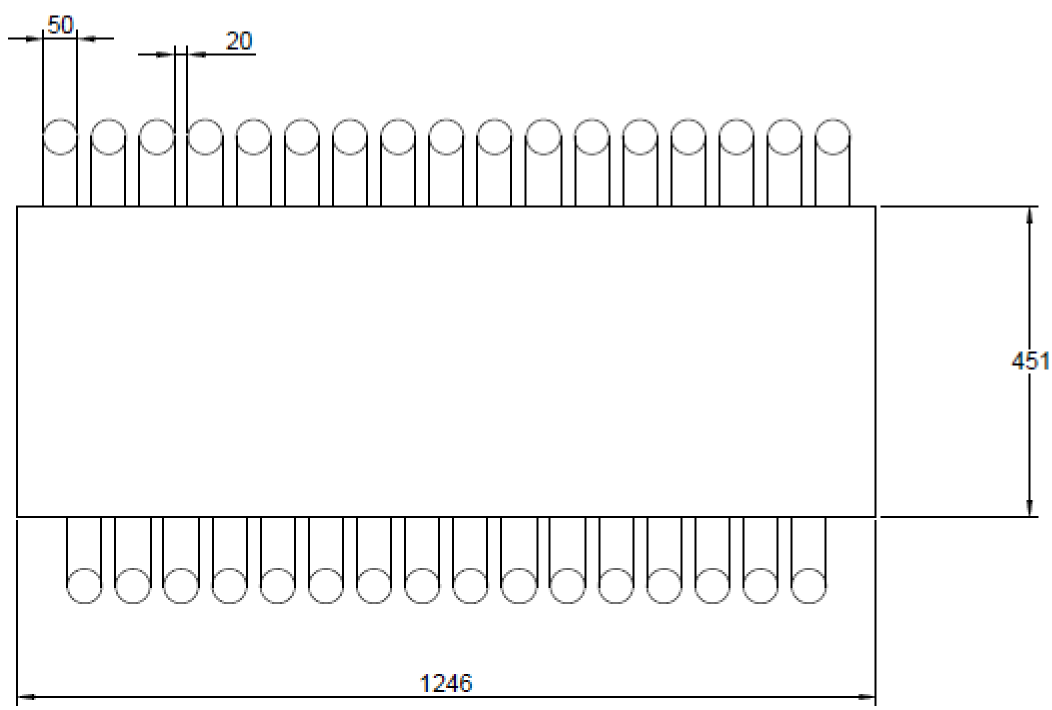


Fig.04:Top View of Transformer with radiator

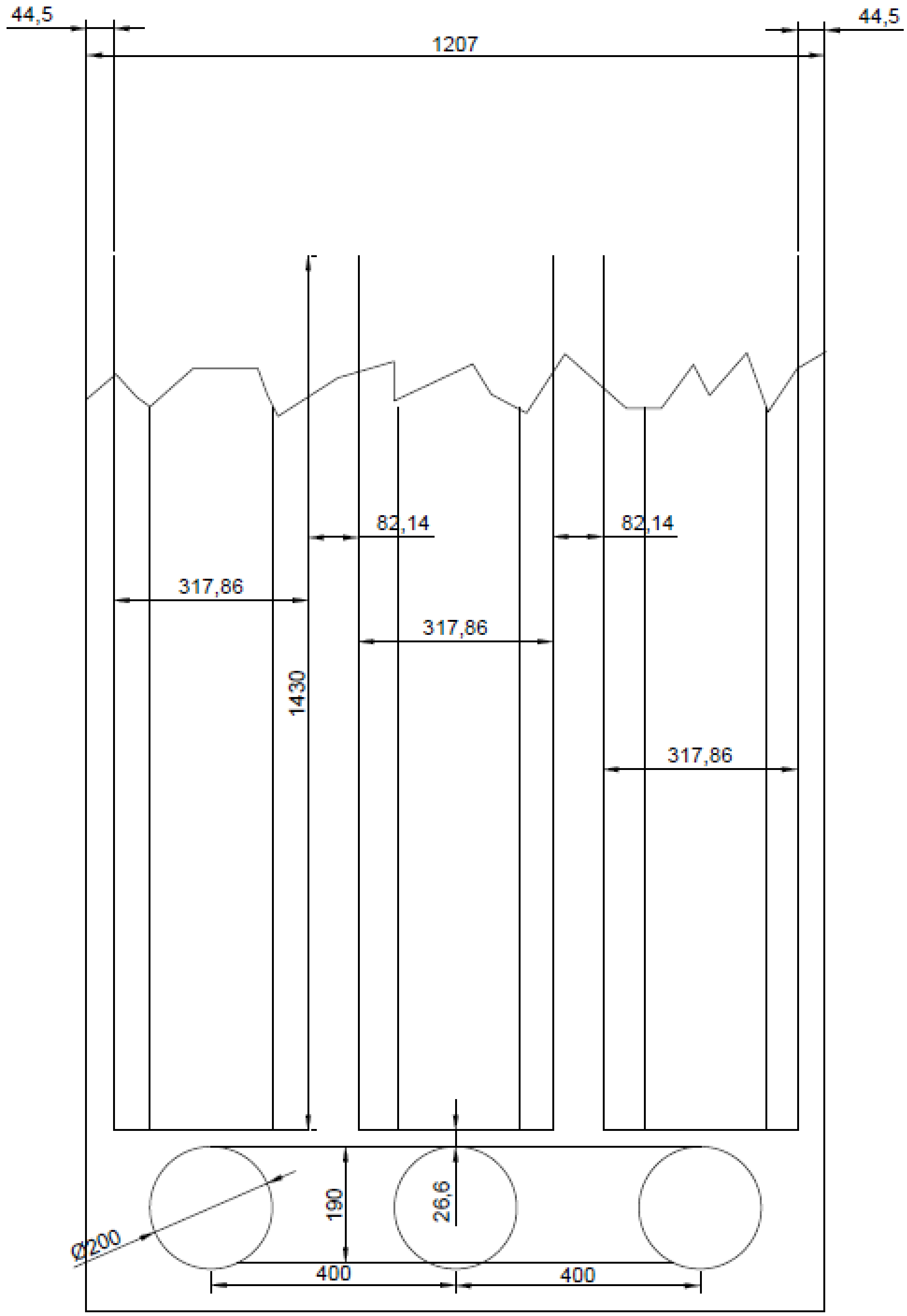


Fig.05: Tank Dimensions

- **Temperature Rise:**

For the dissipation of heat only 4 surfaces of a tank are taken into consideration. The top and bottom are not considered.

Surface of the tank=$\frac{1430}{1000}\times\frac{438}{1000}\times2+\frac{1430}{1000}\times\frac{1207}{1000}\times2$ =4.7m^2

Full load Loss= 5082.874 W=5.08kW

Now,

If 12.5 Watts/m^2/°C temperature rise is taken as dissipation due to convention and radiation

∴The temperature rise=$\frac{5082.874}{12.5\times4.7}$ =86.52°C

Let, Surface area of all cooling tubes = xS_t

The cooling tube will dissipate the heat using convection and it will be 35% more compared to the flat surface.

- Heat dissipated by cooling tubes =6.5×135/100× xS_t =8.8xSt
- Total heat dissipated by transformer tank surface and the cooling tube =(12.5+8.8x)St

Total heat developed inside the machine is equal to total iron losses and heat copper losses.

- Amount of heat developed =Pi + Pcu = 5.08kw
- The temperature rise in transformer is, $\theta = \frac{Amount\ of\ heat\ developed}{Amount\ of\ heat\ dissipated}$

$$= \frac{5.08\times1000}{(12.5+8.8x)St}$$

- Here, Surface of tank, S_t =4.7 m^2
- Temperature of transformer wall may be limited to 45°C.

  Hence, θ =45°C; So**, x=1.31**

- The total number of cooling tubes required = n_t
- $n_t = \frac{Total\ surface\ area\ of\ tubes}{\text{Surface area of each tube}} = \frac{xSt}{\pi\times dt\times lt}$
- Length of tube, l_t = 0.8 h_t =0.8×1430/1000=1.287 m
- Standard diameter of the tube, d_t = 50 mm = 0.05 m
- Center spacing between tube 70 mm

$$\boxed{\therefore n_t = \frac{1.31\times4.7}{\pi\times.05\times1.287} = 30.45 \approx 31}$$

❖ Volume and Weight of Oil

- Volume of tank up to oil level of 1180 mm

$$=\frac{1207}{1000}\times\frac{438}{1000}\times\frac{1180}{1000}$$

$=0.624\ m^3$

- Volume of transformer core and copper

$$=\frac{297.21}{8.89\times1000}+\frac{694.8}{7.85\times1000}=0.1219\ m^3$$

- Volume of Oil= Volume of tank up to oil level- Volume of transformer core and copper

$=(0.624-0.1219)=0.5021\ m^3$

- Oil required in transformer=0.5021×1000L =502.1L ≈502L
- Weight of oil required =502×0.89 = 446.78 kg

❖ Weight of Tank

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

$$\therefore \text{Weight of tank}=0.005\times\left(\frac{1207}{1000}\times\frac{438}{1000}+\frac{1207}{1000}\times\frac{1430}{1000}+\frac{1430}{1000}\times\frac{438}{1000}\right)\times 2\times 7.85\times 1000kg$$

$=226.16kg$

❖ Volume and Weight of Oil in Tubes

- 31 tube each of 50 mm diameter and 1.287 m length.
- Therefore, Volume = $\frac{\pi}{4}\times(50/1000)^2\times 1.287\times31$

  $= 0.0783\ m^3$,
- Volume of oil in tubes= 0.0783 x 1000 = 78.3 L
- Weight of oil in tubes = 78.3 x 0.89 = 69.687kg
- Weight of tube = π x (50/1000) x 1.287 x 0.005 x 31x 7.85 x 1000 kg

  = 245.98 kg

❖ Total Weight of Transformer

• Weight of core and yoke assembly	694.8kg
• Weight of copper in windings	297.21kg
• Weight of tank and tubes	226.16kg
	245.98kg
• Weight of oil in tank and tubes	446.78kg
	69.687kg
Total weight	1980.62kg

SUMMARY

❖ Specifications

Transformer designed as per IS: 6061-1971

kVA	412 kVA
H.V. volts	11kV
L.V. volts(No load)	415 V
H.V. current	12.48A
L.V. current	139A
Phase	3
Connection	Delta/star
Vector group	DY11
Percentage impedance	4.5%
H.V. tapping	±2.5% and ±5%
Frequency	50 cy/sec
Temperature rise over oil	60 ºC
Type of cooling	Oil Natural

❖ Core & Yoke

Material: CRGO (cold rolled grain oriented) steel laminations 0.25 mm thick; mitered core construction 45° cut.
Voltage per turn, 9.3 volts; Flux density B_{max}=1.65 Wb/m^2; Net area of cross-section of core, 25434 mm^2; circumscribing circle diameter 200 mm.

Size of core, yoke, and frame: Yoke made of the same section as the core, 3 limb core construction. Distance between centers of adjacent limbs,400 mm: width of the window, 210 mm; the height of window, 500 mm; Width of the limb 190mm; overall height of frame 880mm; overall width of core frame 990mm.

Weight of core and yoke assembly 801.27 kg;
core loss at $B_{max} = 1.65$ wb/m^2, 1.3 watts per kg ; magnetizing VA = 10 VA / kg

Windings	**L.V.**	**H.V.**
Type of winding	Helical	Dick
Current density	2.5 A/mm^2	2.5 A/mm^2
Cross-sectional area of conductor	230 mm^2	4.992 mm^2
Conductor: Copper	2 strips of 9×12.8 mm	Diameter 2.52 mm
Number Of Layers per limb	1	4 discs
Number of turns	26	1183 Normal 1243 max tapping
Number of turns per layer	26	311
Height of winding in window	340 mm	412 mm
Thickness of coil	18.5 mm	24.93 mm
Inside diameter of coil	207 mm	268 mm
Outside diameter of coil	244 mm	317.86 mm
Mean length of turn	708.43 mm	920.27 mm
Resistance at 75 ºC	0.00168 ohms	4.81 ohms
Weight of copper for winding per limb	37.66 kg	48.31 kg
Total Weight Of Copper	257.91 kg	

❖ Insulator:

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

Insulation for conductors: paper

Insulation between layers: Crape paper

Insulation between LV and HV 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 86.52^{0}C

Inside dimensions of tank: length 1207 mm; breadth 438 mm; height 1430 mm

Tubes 31, each of 50 mm diameter; 1.287m long

Oil in transformer tank	502 liters
Oil in tubes	78.3 liters
Weight of oil in tank	446.78 kg
Weight of oil in tubes	69.887 kg
Weight of tank	226.16 kg
Weight of tubes	245.98 kg
weight of complete transformer	1980.62 kg

❖ Tappings

The tappings on HV Winding.

<table>
<tr><th>Tapping</th><th>5%</th><th>Normal</th><th>2.5%</th></tr>
<tr><td>(+)</td><td>1243</td><td rowspan="2">1183</td><td>1213</td></tr>
<tr><td>(-)</td><td>1124</td><td>1254</td></tr>
</table>

❖ Performance

Percentage resistance	0.948 %
Percentage reactance	3.63%
Percentage impedance	3.75%
Iron loss	903.24 watts
Copper and stray load loss, i.e. load loss at 75^{o} C	4179.634watts
Total loss on full load	5082.874 watts
Efficiency on full load at unity power factor	98.78%
Efficiency on 3/4 th full load at unity power factor	98.99%
Efficiency on 1/2 full load at unity power factor	98.96%
Regulation on full load at unity power factor	0.9%
Regulation on full load at 0.8 power factor lagging	2.94%
Core loss current per phase	0.027 A
Magnetizing current per phase	0.2105 A
No load current per phase	0.212 A 1.699% of full load current

❖ Additional Figures:

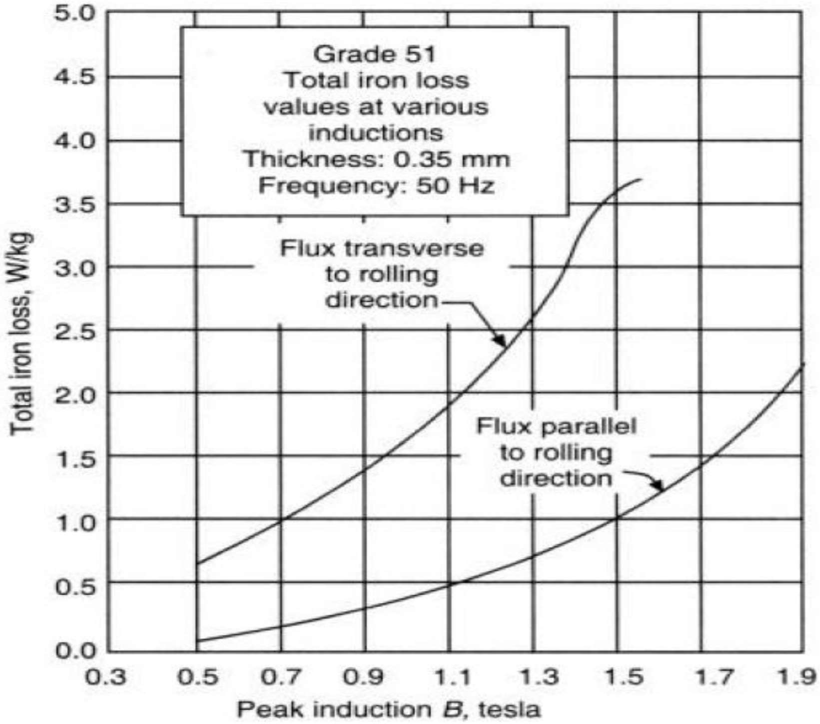


Fig.6: Total iron loss(W/kg) Vs peak induction B(tesla)

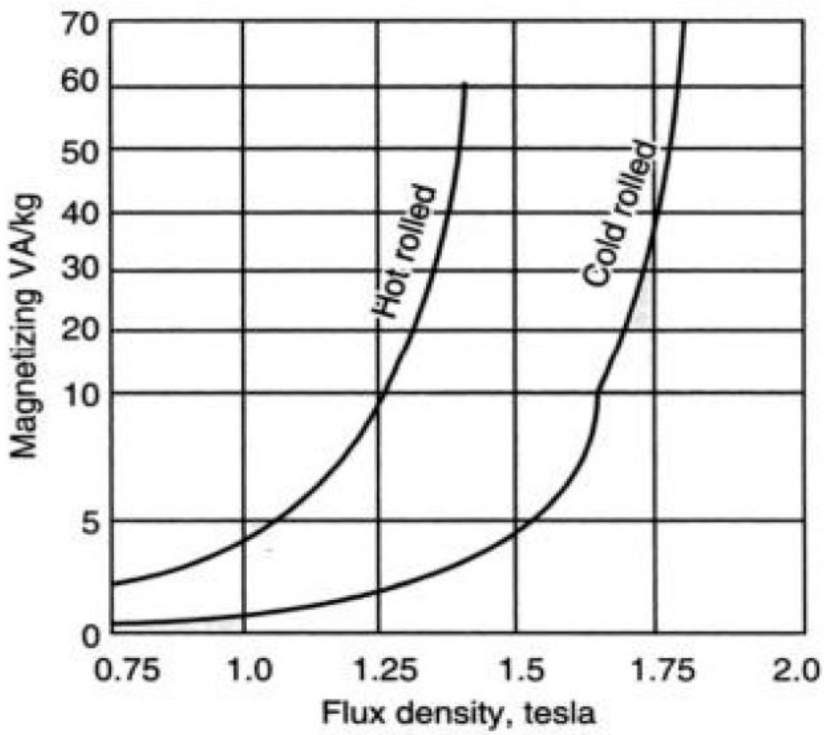


Fig.7: Magnetizing VA/kg VS Flux density(tesla)