EEE-352

Electrical Machine Design

Reference Book

✓ **Design & Testing of Electrical Machines**

By M. V. Deshpande

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Every student is required to **bring this book** from next class. **Otherwise,** he/she will be noted as "**Absent**".

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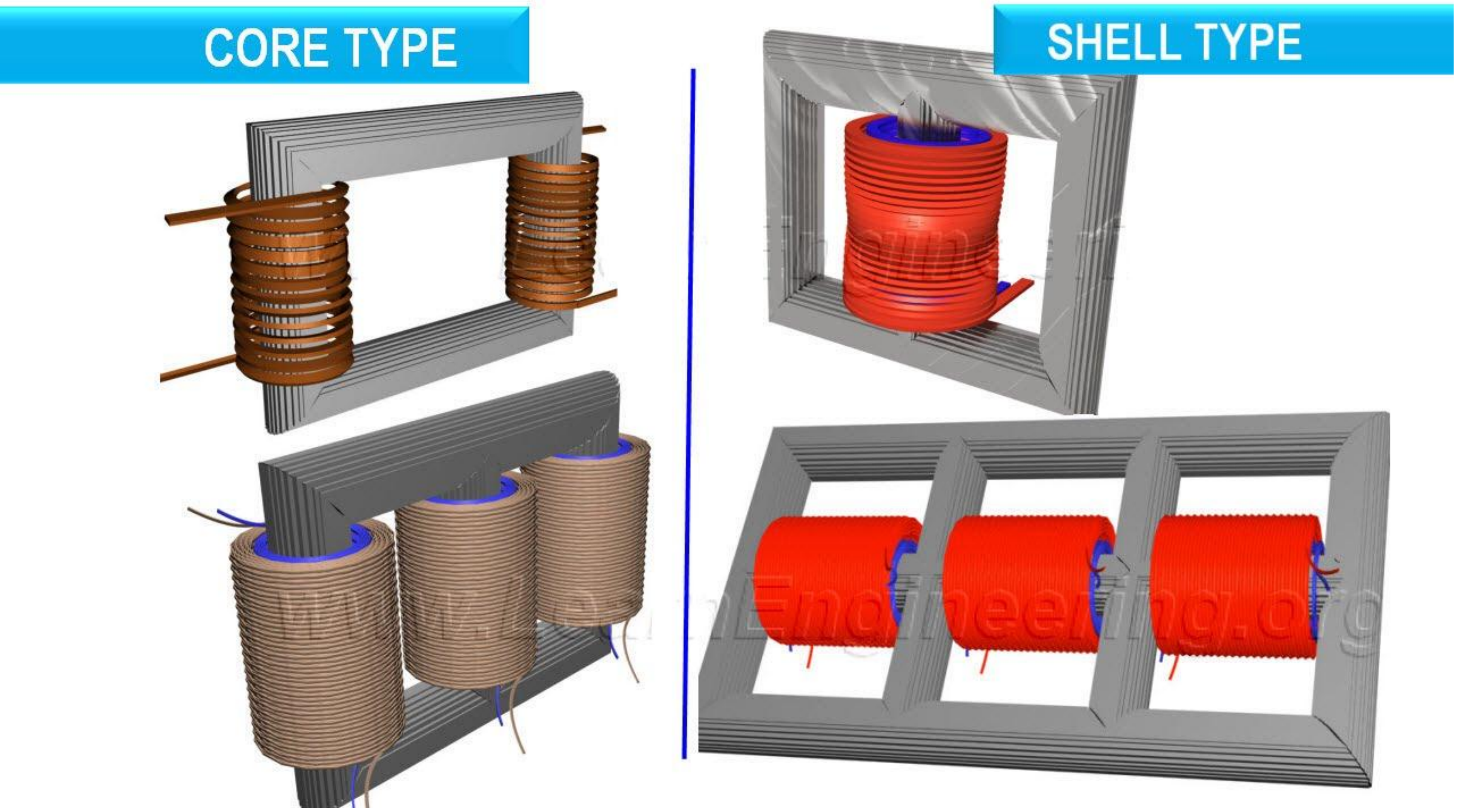
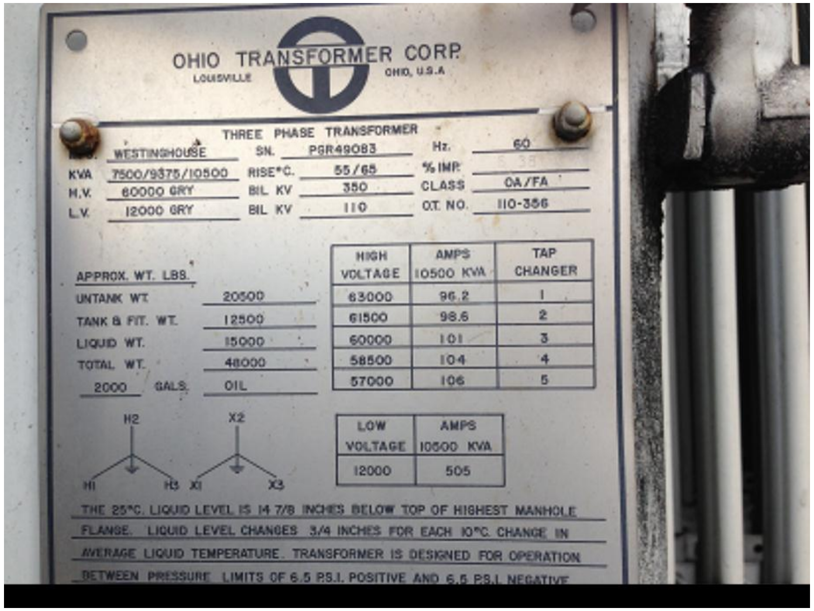
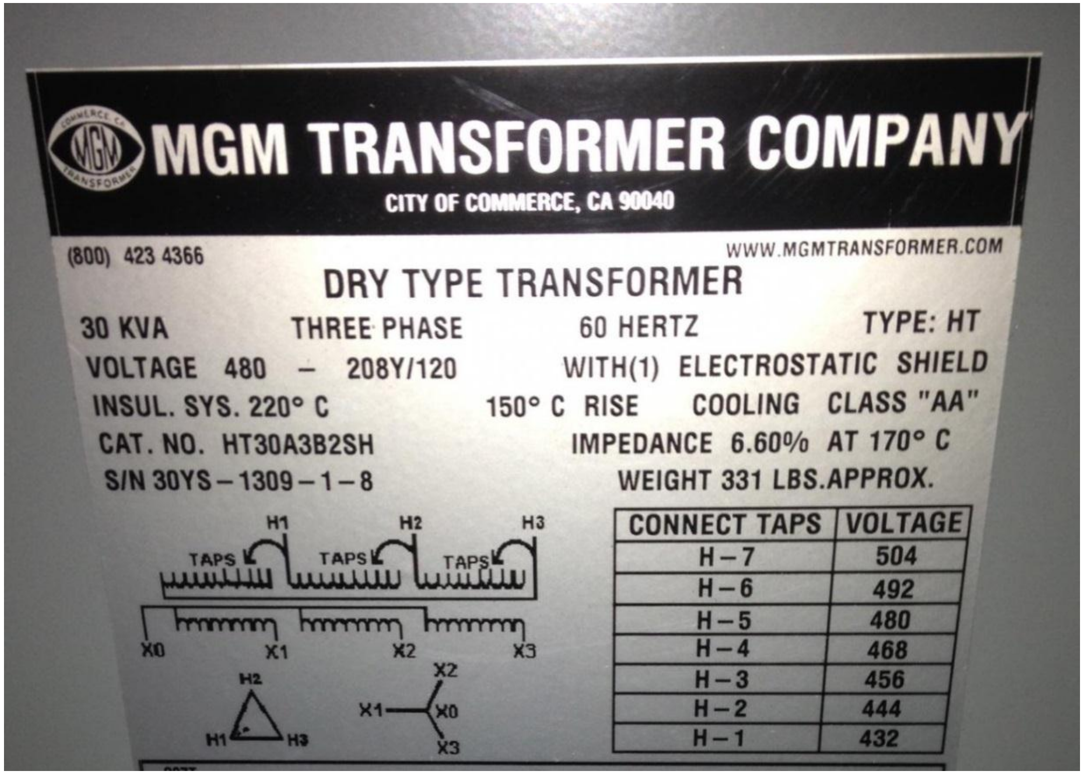
Core Type and Shell Type Transformer



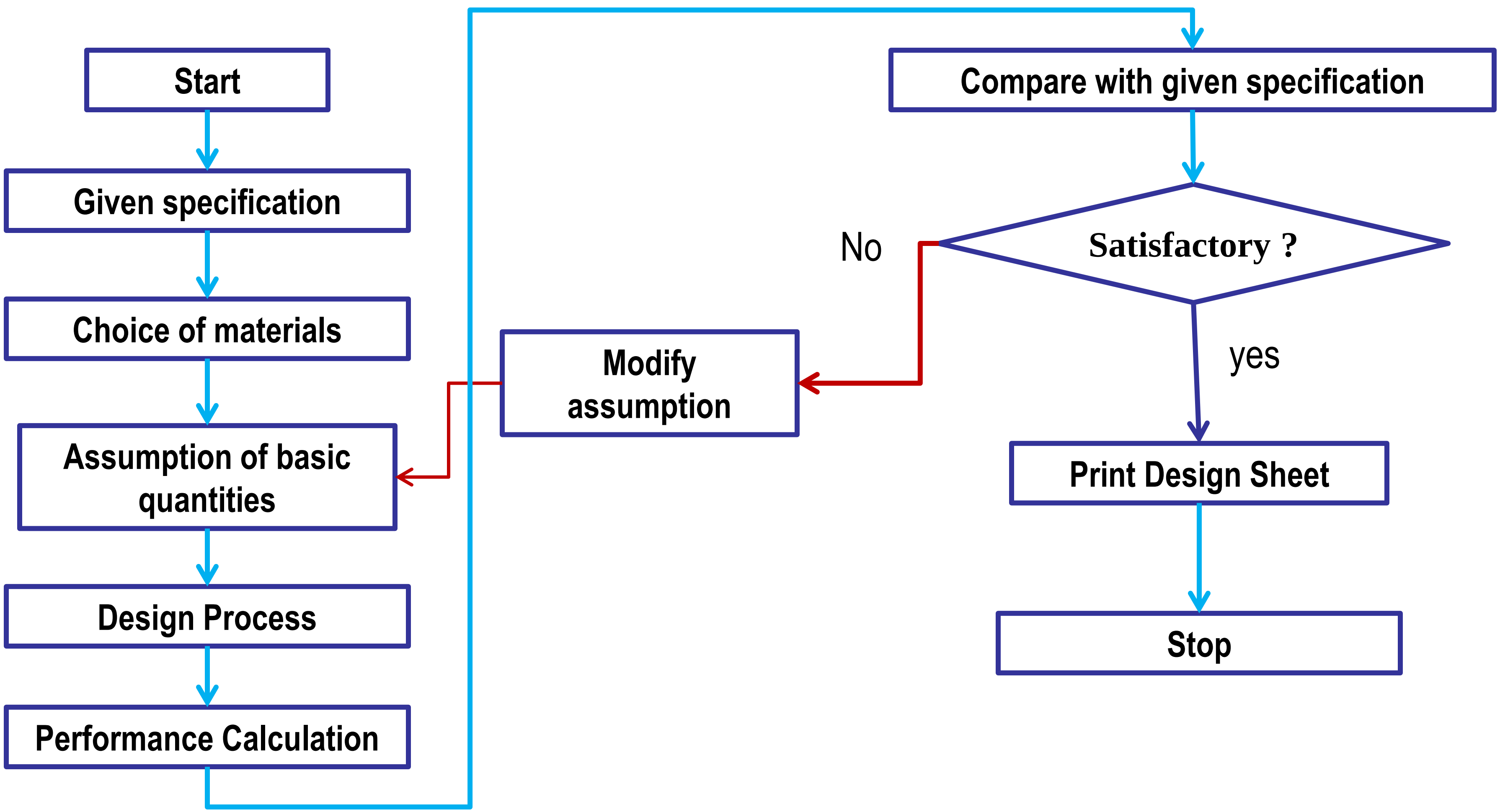
Power Transformer and Distribution Transformer

Transformer Specifications & Nameplate





Design flow chart



Design flow chart

Start

1. Generator
2. Motor
3. Transformer

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Given specification

Performance requirements as needed by the customer's and BDS, ASA, BSI, IEC, IEEE

(Bangladesh Standards and Testing Institution,
American Standards Association, British Standards Institution,
International Electrotechnical Commission,
Institute of Electrical and Electronics Engineers)

↓

Choice of materials

1. Magnetic (HRS, CRS, CRGOS, etc)
2. Conducting (Cu, Al, etc)
3. Insulating Material

↓

Design flow chart

Assumption of basic quantities

1. Specific magnetic loading
2. Specific electrical loading
3. Space factor
4. Staking factor/ Lamination factor

Design Process

Analysis and Calculations to determine:

1. Magnetic circuit
2. Electric circuit
3. Thermal and Mechanical design

Performance Calculation

Design flow chart

Assumption of basic quantities

1. Specific magnetic loading
2. Specific electrical loading
3. Space factor
4. Staking factor/ Lamination factor

CHOICE OF MAGNETIC LOADING (B_m)	
Normal Si-Steel (0.35 mm thickness, 1.5%—3.5% Si)	0.9 to 1.1 T
HRGO (Hot Rolled Grain Oriented Si Steel)	1.2 to 1.4 T
CRGO (Cold Rolled Grain Oriented Si Steel) (0.14---0.28 mm thickness)	1.4 to 1.7 T

CHOICE OF ELECTRIC LOADING (δ)		
Natural Cooling:	1.5---2.5 A/mm^2	
	AN	Air Natural cooling
	ON	Oil Natural cooling
	OFAN	Oil Forced circulated with Natural air cooling
Forced Cooling :	2.2---4.0 A/mm^2	
	AB	Air Blast cooling
	OB	Oil Blast cooling
	OFAB	Oil Forced circulated with air Blast cooling
Water Cooling:	5.0 ---6.0 A/mm^2	
	OW	Oil immersed with circulated Water cooling
	OFW	Oil Forced with circulated Water cooling

Design flow chart

Performance Calculation

1. Predetermination of performance of the machine is then made based on the calculated dimensions.
2. Performance are calculated [No-load, On-Load conditions and temperature rise etc.]

Compare with given specification

1. Compare with customer's requirement.
2. If not, designer has to modify the basic assumption so as to bring the final design closer to the objective.

Print Design Sheet

STANDARDIZATION AND STANDARDS

Standardization and standards play an important part in the choice, design, manufacturer and operation of any apparatus.

1) To the manufacturer it means reduction in cost (a number of objects are built at the same time)
2) To the user, it means interchangeability of equipment's
3) To the designer, it means rigidity.

Design procedure of distribution transformer

1) Specification of the transformer to be design
2) Assumption of basic quantities (E_t, B_m, δ)
3) Design of Main dimension (A_i, D, A_w, k_w)
4) Design of winding (T_1, T_2, a_1, a_2)
5) Design winding layout (no. of turn per layer, no of coils, clearance between core & LV, LV & HV, HV & tank etc.)
6) Design core frame, core dia, widow, yoke, oveall core size
7) Calculate % R, %X, %Z
8) Calculate magnetizing VA, No-load loss, Cu loss, stray loss and load loss at 75^0C
9) Calculation of performance
10) Thermal design (Design of Tank, Radiator)

Objective of this Class

- **To Design a distribution transformer**

Design Example:

"Design a **100 kVA**, 3 phase, 50 Hz, **11 KV/415 V**, delta/star distribution transformer. Tapping ± 2.5%, ± 5% on high voltage side. Cooling ON (self oil cooled); **Temperature rise over oil 50^0C**. No load loss not more than **250 watts**; copper and stray load loss not more than **2000 watts**. Percentage **impedance 4.5%.** Calculate: No load current, efficiency at 75^0C on full load,75% load and 50% load at unity power factor; Voltage regulation on full load at 75^0C at unity power factor and at 0.8 power factor lagging".

Design of a **100 kVA**, 3φ distribution transformer

- Voltage per turn: E_t

$$E_t = \frac{\sqrt{\left(\frac{kVA \times 1000}{no.of\ legs}\right)}}{40}$$

This is an empirical expression which gives E_t fairly accurate. Here, $no.\ of\ legs$ for this three phase core type transformer is 3

Hence,

$$E_t = 4.56 \cong 4.5\ volts/turn$$

- Choice of core material: CRGO steel lamination of 0.35mm

- Choice of specific magnetic loading, B_{max}: 1.7 Wb/m^2

Design of a **100 kVA**, 3φ distribution transformer

- Cross Section area of the core A_i:

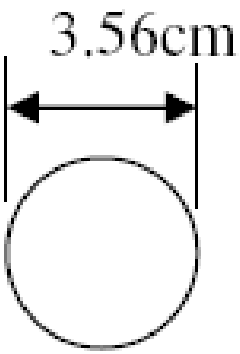
We know, $E_t = 4.44 \times B_m \times f \times A_i$

Where, $B_m =$ flux density in wb/m^2; $f = 50$ Hz and

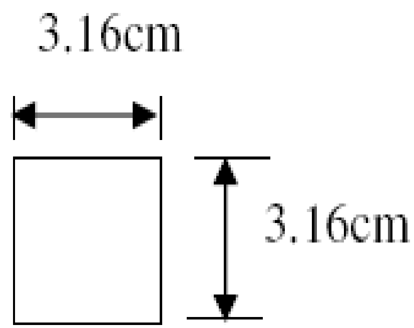
$A_i =$ net cross section area of the core

$$\boxed{\begin{aligned} A_i &= \frac{E_t}{4.44\, f\, B_m} \\ &= \frac{4.5}{4.44 \times 50 \times 1.7} = 0.01192\, m^2 \\ &= 11{,}923\, mm^2 \end{aligned}}$$

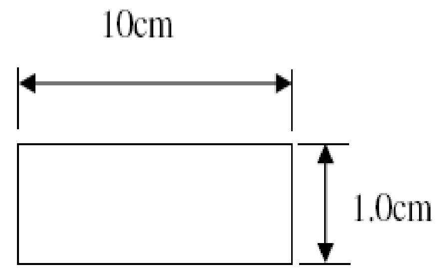
Choice of core section



Circular core :
- If the area is $10cm^2$,
- then the diameter of the core =3.56cm and
- the Circumference = πx3.56=11.2 cm



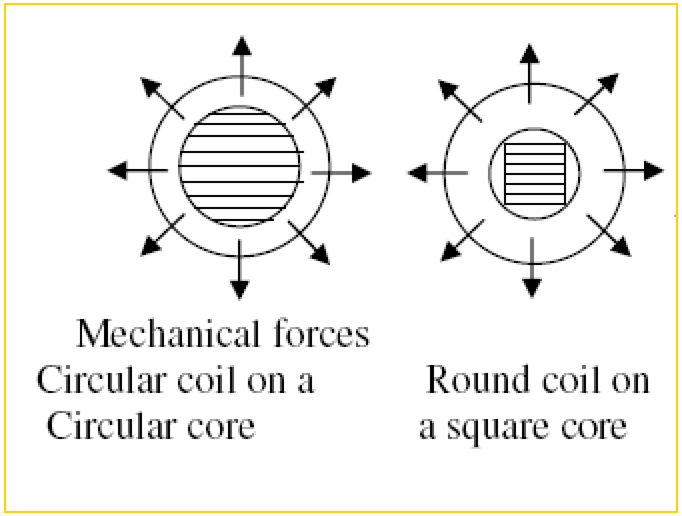
Square core :
- for Ai = $10cm^2$,
- side of the square = 3.16 cm
- Perimeter = 4x3.16=12.64cm

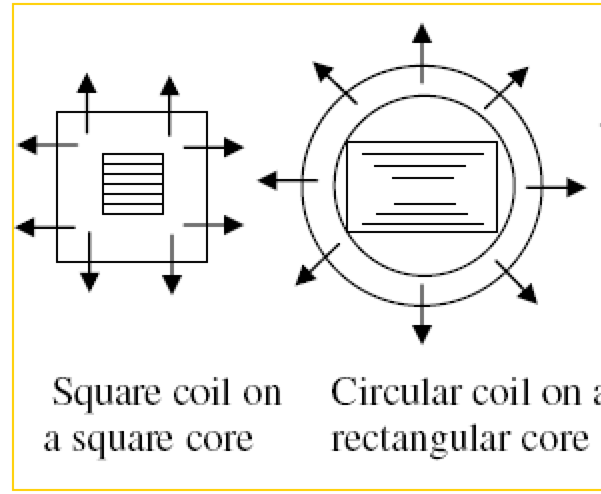


Rectangular core:
- for Ai = 10 cm^2 ,
- sides of the rectangle to be 10cm and 1.0cm
- Perimeter = (10+1)2=22cm

➢ Which type of core is preferable for transformer design? And why?

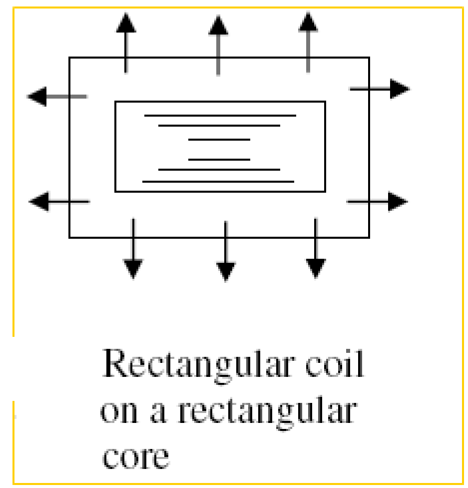
Choice of core section



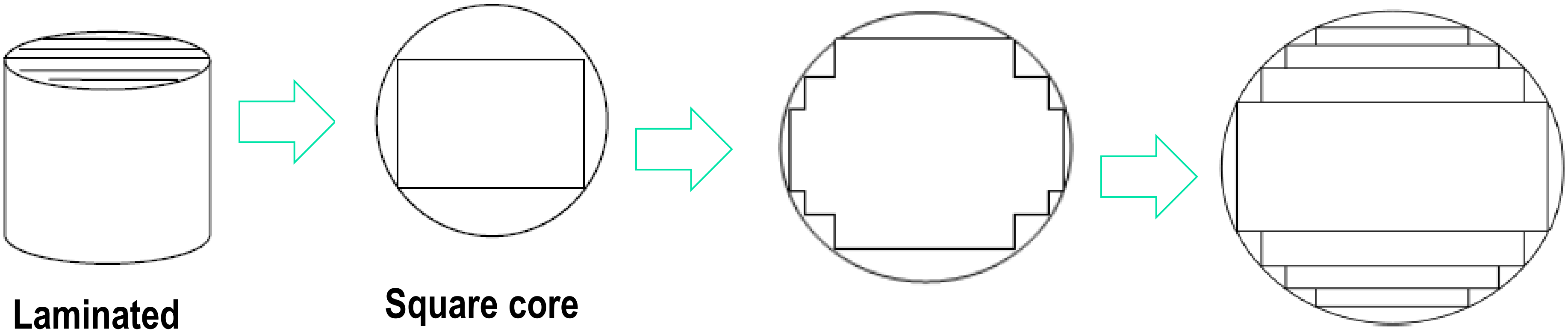


Another reason….

- ❑ Very high value of mechanical forces tries to deform the shape of the square or rectangular coil (the mechanical forces try to deform to a circular shape) and hence damage the coil and insulation.
- ❑ Since this is not so in case of circular coils, circular coils are preferable to square or rectangular coils.



Selection of the no of step in core design.



Laminated circular core

Square core

Three stepped core

Four stepped core

- ❑ Thus a circular core and a circular coil is preferable.
- ❑ Since the core has to be of laminated type, circular core is not practicable as it required more number of different size laminations and poses the problem of securing them together is in position.
- ❑ However, a circular core can be approximated to a stepped core having different number of steps.
- ❑ In practice the core is built of 0.35 mm thin strips arrange in a number of steps.
- ❑ By increasing the no of steps, the area of the circumscribing circle is more effectively utilized.
- ❑ Iron space factor for typical number of steps in core is presented table 6.4, Page 147 [Deshpande]

Design of a **100 kVA**, 3φ distribution transformer

➢ Diameter of the circumscribing circle for the core: d

- ❑ Chosen seven step cores so, the area should be nearly circular. In the case of a 7 step core,
- ❑ Iron space factor, $K_i = 0.88$ and
- ❑ Stacking factor for laminations, $K_s = 0.92$

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

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

$$d^2 = \frac{4 \times 11923}{0.88 \times 0.92 \times \pi}$$

$$d^2 = 18760\ mm^2$$

$$d = 136.96$$

Choose $d \approx 140$ mm

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

$$= 12{,}456\ \text{mm}^2$$

Design of a **100 kVA**, 3φ distribution transformer

➢ Check B_m:

With this area $A_i = 12{,}456\ mm^2$

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

$$= \frac{4.5}{4.44 \times 50 \times 12463 \times 10^{-6}} = 1.63\ \text{Wb}/m^2$$

➢ Window area A_w:

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

$$A_w = \frac{S}{3.33 \times A_i \times k_w \times \delta \times B_m \times f \times 10^{-3}}\ mm^2$$

Here,

K_w = Window space factor (k_w)

Empirical formula is used for k_w

See, Art 6.6 and Table 6.5 page 149 [Deshpande]

K_w is taken approximately 0.29

A_w = Window area ?

A_i = net cross section area of the core, m^2

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

S = output in kVA (100 kVA) ;

➢ **Therefore, A_w = 40,779 mm^2**

Design of a **100 kVA**, 3φ distribution transformer

Core and Window Dimensions:

Choose window width $=150$ mm (about d); then height of window $=\frac{40779}{150}=272$ mm. Choose height of the window $=$ $2\times$ width of window approx. $=150\times2=300$ mm checking clearance to yoke. This is later taken as 334mm

Then window area $=300\times150=45000\text{mm}^2$

The main dimensions of the core are therefore : diameter $d=140$ mm; $D=$ distance between the centres of the adjacent limbs $=150+133=283$ mm; with a 7 step core, the largest width of the core with $d=140$ mm is $0.95\times140=133$ mm. Fig. 6.8 shows the core and yoke assembly dimensions.

Design of a **100 kVA**, 3φ distribution transformer

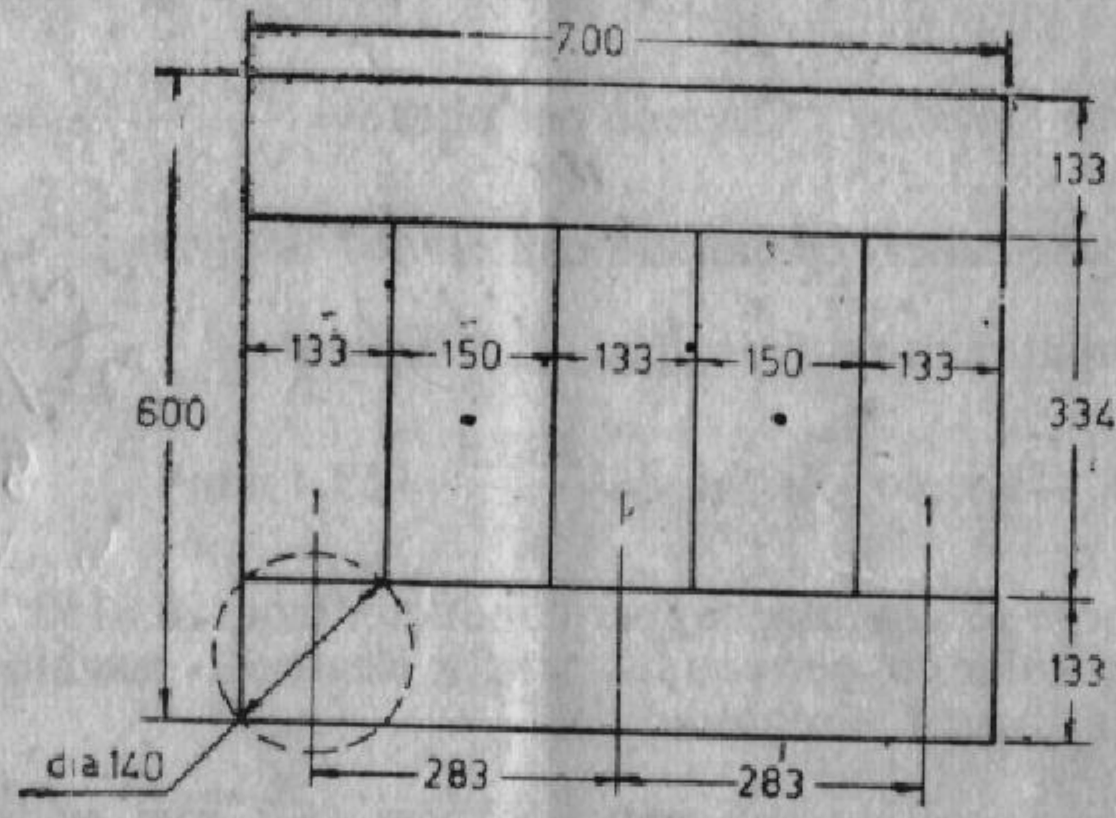


Fig. 6.8. Core and assembly for example 6.1

Height of window $= 334$ mm; total width $= (2 \times 283) + 133 = 699$mm

$\simeq 700$mm

Total height $= 334 + 133 + 133 = 600$ mm

DESIGN OF WINDINGS

Number of turn in L.V. winding: **(Δ-yn)**

Voltage per phase = 415 / √3 = 239.6 V [*L.V. is Y connected*]

Turns per phase on l.v winding = 239.6 ÷ 4.5

=53.24 turns, choose 54 turns.

Number of turns of H.V. winding: **(Δ-yn)**

Voltage per phase = 11 KV [*H.V. is Δ connected*]

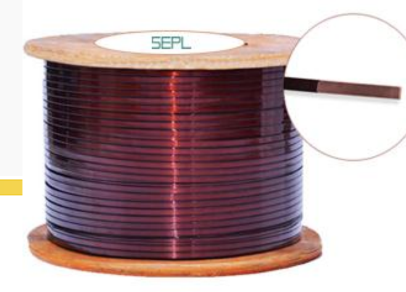
Turns per phase on h.v. winding = $11 \times 10^3 \div 4.5 = 2444.44$

= chosen as 2445 turns.

Tapings of ± 5% and ± 2.5% are to be provided on the h.v. winding.

	5%	Normal	2.5%	
More	2568	2445	2383	turn
Less	2506		2322	turn

DESIGN OF WINDINGS



LOW VOLTAGE WINDING: **(Δ-yn)**

Current per phase = $(100\times 10^3) \div \{(\sqrt{3}) \times 415\}$ = 139 A

Here, choose helical cylindrical coil.

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

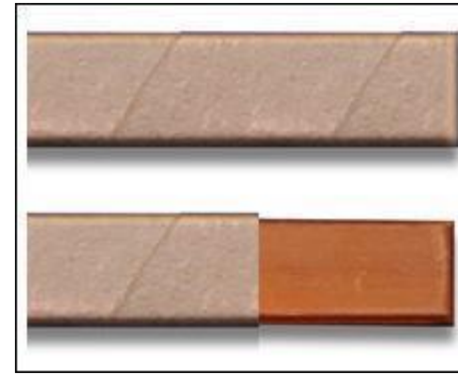
- ✓ Area of L.V. conductor, $a_2 = 139 \div 2.5$
  $= 55.6\ mm^2 \cong 56\ mm^2$

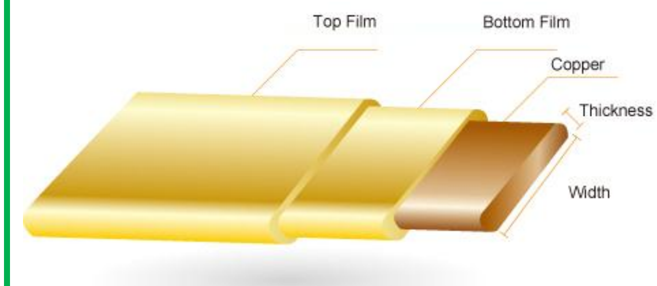
Choosing, rectangular copper conductor from IS:6160:1977 specs.

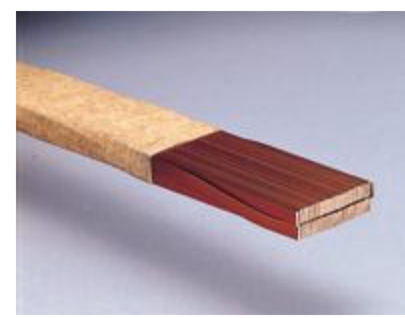
Let, Cross Section = T × W = 4 mm × 7 mm;
2 conductor strips

Therefore,

Forming conductor of L.V. area, $a_2 = 4\times7\times2\ mm^2$;
$= 56\ mm^2$







DESIGN OF WINDINGS

High voltage winding: (Δ-yn)

Choose disc coils.

current in H.V. winding per phase

$= (100\times 10^3)\div(3\times 11\times 10^3)$

$= 3.03$ A

Cross section of conductor for H.V. winding ,

$\mathbf{a_1} = 3.03 \div 2.5 = 1.21\ \text{mm}^2$

DESIGN OF WINDINGS

Choosing round conductor where,

d = diameter of conductor

$\mathbf{a_1} = \pi d^2 \div 4; \quad d^2 = 1.54;$

Therefore, **d** = 1.212 mm

Now choosing, d = 1.25 mm;

Then area, $\mathbf{a_1} = 1.23\ mm^2$

Copper area in window = $2\,(a_1T_1 + a_2T_2) = 2\,(1.23 \times 2568 + 54 \times 56)$

$= 12{,}365.28\ mm^2$

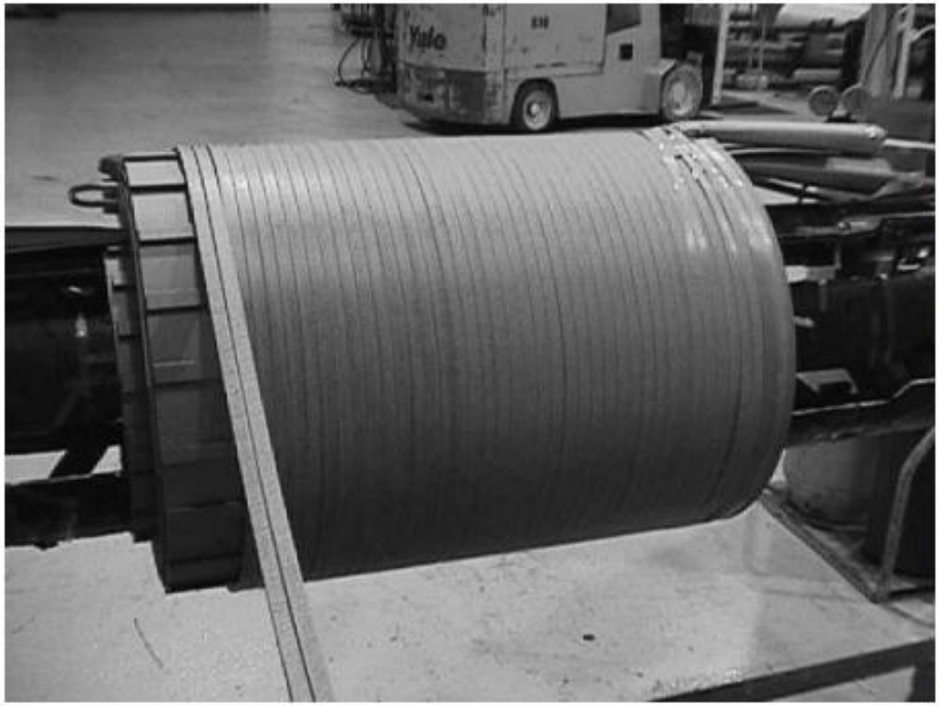
Now for this dimensions, we get, window space factor,

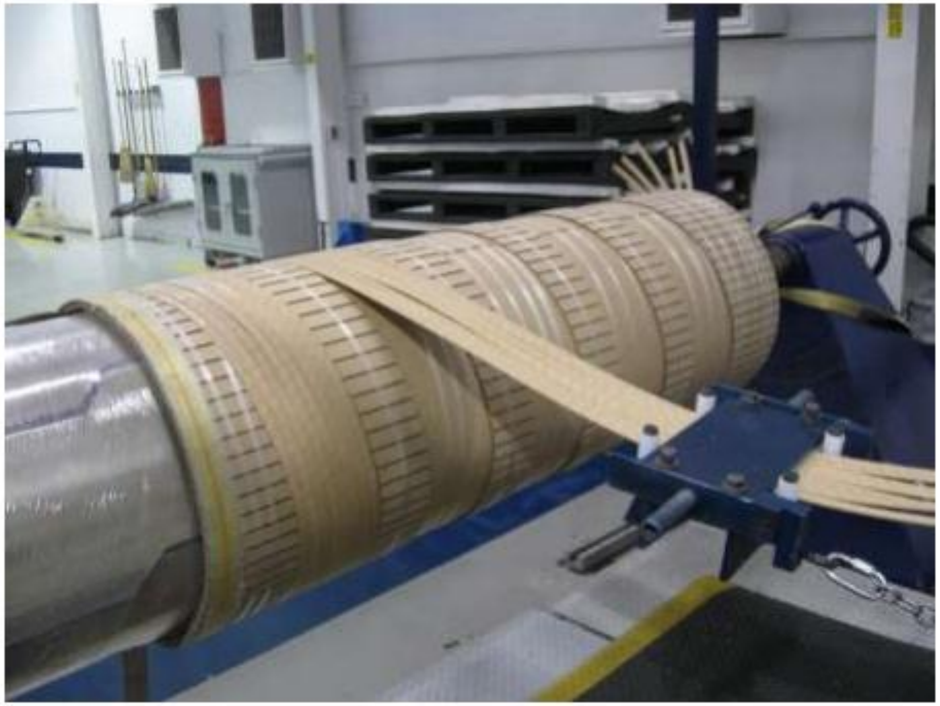
$k_w = (12{,}365.28 \div 40{,}800) = 0.3$

which is near about 0.29 (chosen)

Winding Types

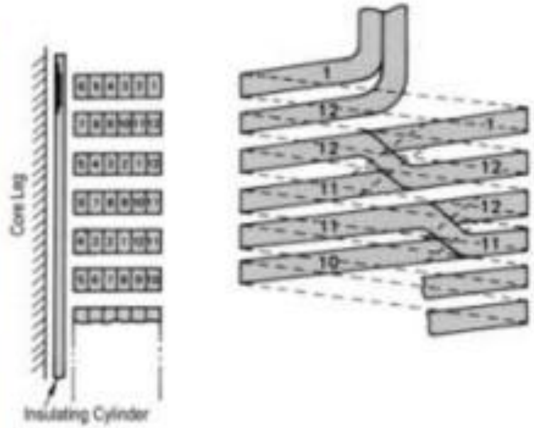
SLL / Layer / Barrel





Winding Types (cont.)

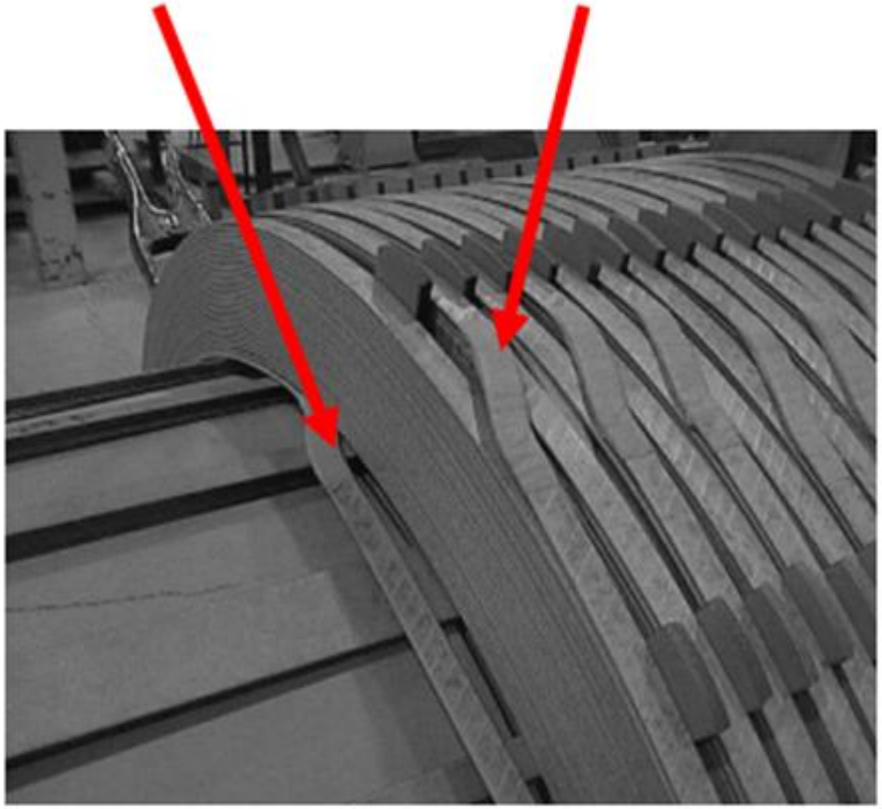
Helical / Screw

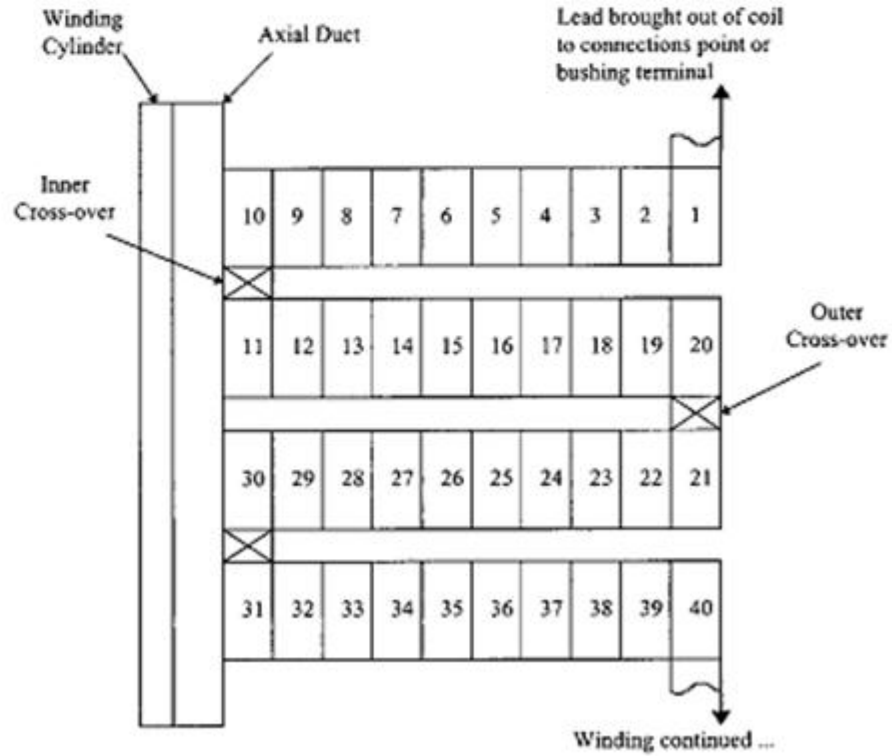


Winding Types (cont.)

Continuous Disk Winding

Inner cross-over   Outer cross-over





For more: *http://electrical-engineering-portal.com/power-transformer-construction-windings*

DESIGN AND LAYOUT OF L.V. WINDING

- Number of turns in L.V= 54.
- Size of conductor : 2 strips of 4×7 mm ,
- Consider paper insulation of conductor is = 0.25 mm;
- With paper insulation: 2 strips of conductor (4+ 0.25) mm × (7 + 0.25) mm

- Choosing 2 layers for L.V. winding, Turns per layer = 54 / 2 = 27
- Width of conductor 7.25 mm is taken along the window,
- with 2 conductor sides 4.25 + 4.25 = 8.5 mm forming conductor per layer.
- For two layers, the dimension of conductors width wise is 17 mm

DESIGN AND LAYOUT OF L.V. WINDING

- height of l.v. winding in window= 27×7.25= 195.75mm; say 196 mm;
- thickness of l.v. coil = 8.5× 2 = 17 mm
- distance between core and l.v. coil = 3.5 mm
- inside diameter of l.v. coil = 140+ (2 × 3.5) = 147 mm
- outside diameter of l.v. winding = 147 + (2 × 17) = 181 mm
- mean diameter of l.v. coil = 147 + 17= 164 mm
- mean length of turn of l.v. coil =πd= 164× π = 515 mm

DESIGN AND LAYOUT OF L.V. WINDING

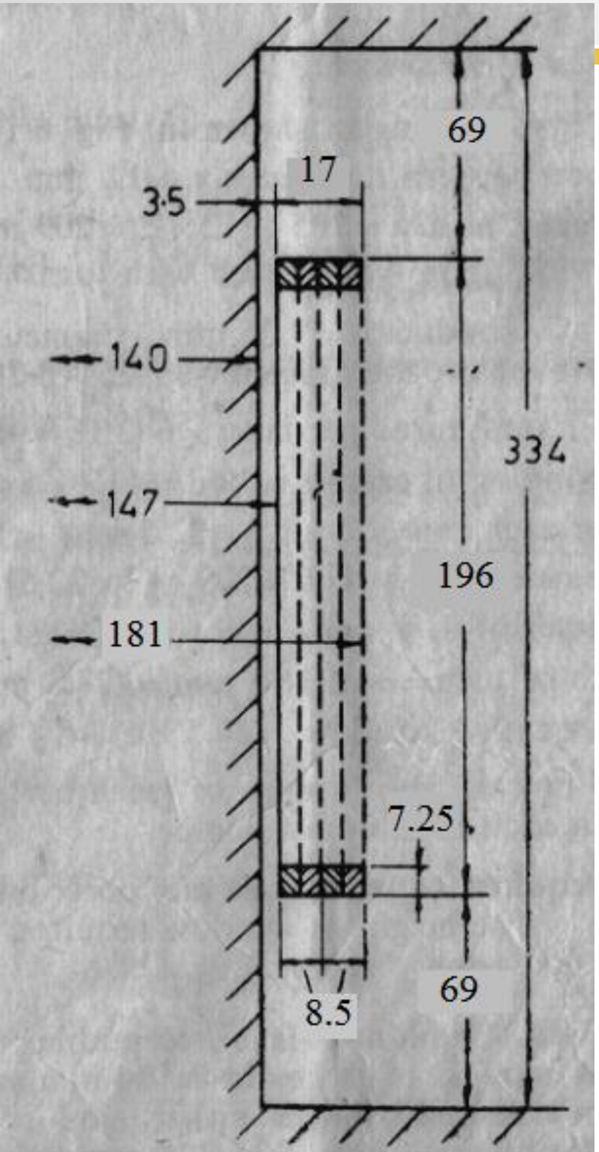


Fig. 6.9. Layout of l.v. winding

DESIGN AND LAYOUT OF H.V. WINDING

- The distance between L.V. and H.V. = 12 mm
- Inside diameter of h.v. = 181 + (12× 2) = 205 mm
- Now, Split h.v. winding in 4 coils each with turns = 2568/4 = 642
- The size of conductor = 1.25 mm diameter.
- With paper insulation on conductor, the diameter = (1.25 + 0.25) mm= 1.50 mm

DESIGN AND LAYOUT OF H.V. WINDING

- Choose 15 layers ; turns per layer = 642/15 $\cong$ 43
- height of winding in each h.v. coil = 43× 1.5 = 64.5 mm
- thickness of each coil = 15 × 1.5 = 22.5 mm
- outside diameter of h.v. coil = 205 + (2×22.5) = 250 mm
- mean diameter of h.v. coil = 205 + 22.5 = 227.5 mm
- mean length of turn =π×d=227.5× π = 714.35 mm
- height of h.v. coils in window = (64.5× 4) +**8+8+8** = 282 mm
- The space required between coils and core on either side is taken as 26 mm.
- The height of window required:= 282 + 26× 2 = 334 mm ; Which is acceptable

DESIGN AND LAYOUT OF H.V. WINDING

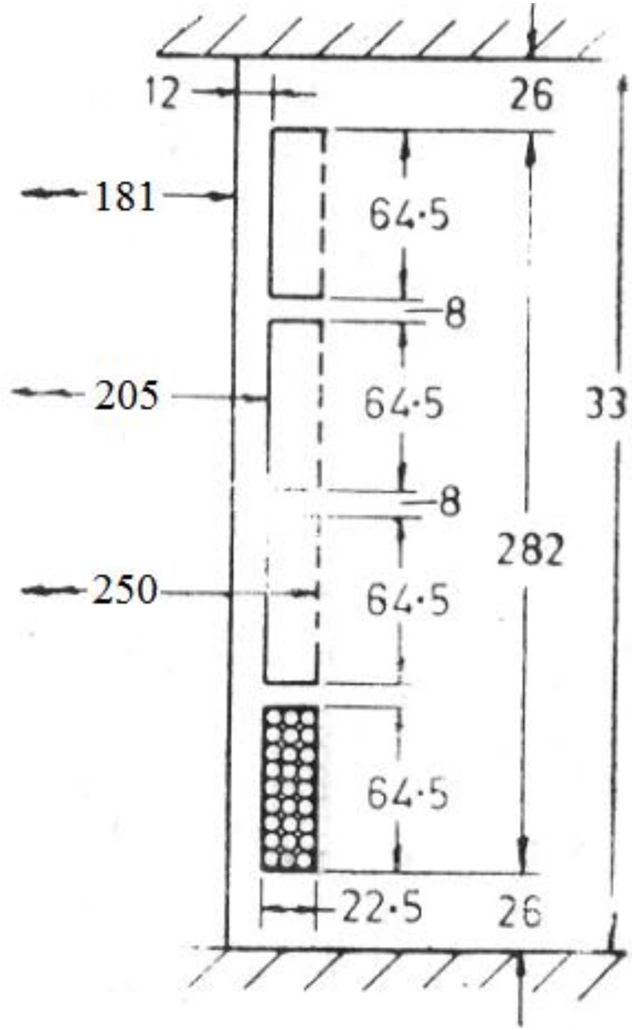


Fig. 6.10. Layout of h.v. winding

PERCENTAGE REACTANCE

L.V. mean length of turn= 164× π = 515 mm

H.V. mean length of turn = 227.5× π = 714.35 mm

$$Average, L_{mt} = \frac{515+714.35}{2} = 614.67\, mm$$

$$AT = 139 \times 54\ ;(L.V.Amp\ \&\ L.V.Turn) = 7506$$

$$mean\ height\ \text{of coils,} \mathrm{h_c} = \frac{196+282}{2} = 239\, mm$$

$$a = 12mm, \mathrm{b_1} = \text{width of h.v.} = 22.5; \mathrm{b_2} = \text{width of l.v.} = 17\text{mm}$$

$$\mathrm{a} + \frac{\mathrm{b_1} + b_2}{3} = 12 + \frac{22.5+17}{3} = 25.16\, mm$$

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

$$= \frac{2\pi \times 50 \times 4\pi \times 10^{-7} \times 0.6146 \times 7506 \times 0.02516}{0.239 \times 4.5} = 0.04256\ p.u.$$

$$or;\ \ \%\, X = 4.256\%$$

PERCENTAGE RESISTANCE

We Know,

$\rho_{20} = 0.01724\ \Omega/\text{mm}^2/\text{m}$ and $\alpha_{20} = 0.00393$

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

  $= 0.01724(1+0.00393\times 55);$

  $= 0.021\ \Omega/\ \text{mm}^2/\text{m}$

- Resistance of low voltage (l.v.) winding: (per phase) ($R=\rho L/\underline{A}$)

  $= (0.021 \times 515\times 54) \div (56\times 1000)\ \Omega$

  $= 0.01043\ \Omega$ (per phase)

- Resistance of high voltage (h.v.) winding: (per phase) ($R=\rho L/\underline{A}$)

  $= (0.021 \times 714.35\times 2568)\div(1.23\times 1000)\ \Omega$

  $= 33.32\ \Omega$ (per phase) **(calculation error)**

PERCENTAGE RESISTANCE

Here, Ratio of transformation = $(11\times 10^3) \div (239) = 46$

And, L.V. winding: 0.01043 Ω (per phase)

Resistance of H.V. winding: 33.32 Ω (per phase)

Now,

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

$$R = 33.32 + 0.0104\times (46)^2\ \Omega$$

$$= 33.32 + 21.92\ \Omega$$

$$= 55.32\ \Omega$$

Percentage of Impedance

- Percentage resistance
- % R =(Eq. Resistance / Base Resistance) ; [Base R= h.v. Voltage/h.v. Current]

  $= (55.32) \div (11\times 10^3/3.03) \times 100\%$

  $= 1.65\%$

Here,

- % X = 4.25 %
- % R = 1.65%

Therefore,

Percentage impedance, $\%Z = \sqrt{(4.25^2 + 1.65^2)} \times 100\%$

$= 4.6\ \%$

N.B: % Z is beyond expectable limit (3.5-4.5%)!!!

So change your dimension

Change window for improving % Z

$$\left.\begin{aligned} W_w &= 0.7\times140 = 98 \approx 102mm \\ L &= \frac{A_w}{W_w} = \frac{40779}{102} = 400\,mm \end{aligned}\right\} \text{And } A_w = 40{,}800\,mm^2$$

D= Distance between center of adjacent limb
= $d+W_w$

Choosing desire window width:

W_W= 0.7xd=0.7x140 = 102 mm
H $\Rightarrow$ L = 400 mm
m_w = 12+5+14=31 $\cong$ 30mm
H_y =28 mm
D= 140x0.95+102 =235 mm

Height of window H = 400 mm;
Clearance to yoke=30 mm
Then, Height of window H =400 + 28 × 2=456 m;
Total width = (2 × 235) + 133 = mm=603 mm ;
Total height = 400 + 133+133 = 666 mm;

Where
W_w=width of window
H_w=Height of window
H_y= Height of the yoke
H=Overall height of frame
=H_w+2H_y
W=Overall width of frame
=2D+a

Change Design layout of L.V. winding

- ❑ Number of turns in L.V= 54.
- ❑ Size of conductor : 2 strips of 4×7 mm , If, paper insulation of conductor=0.25 mm;
- ❑ With paper insulation for conductors,

$= (4+ 0.25)\text{ mm} \times (7 + 0.25)\text{ mm}; =(4.25 \times 7.25)\text{ mm}$

$= \ 30.81\text{ mm}^2$

- ❑ Choosing single layers for l.v. winding,
- ❑ Turns per layer = 54
- ❑ Width of conductor 7.25 mm is taken along the winding,
- ❑ with 2 conductor sides 4.25 + 4.25 = 8.5 mm forming conductor per layer.
- ❑ For single layers, the dimension of conductors,
- ❑ width wise is 8.5 mm and

- ➢ height of l.v. winding in window = $54\times7.25 = 391.5$ mm; say 392 mm;
- ➢ thickness of l.v. coil = $8.5\times 1 = 8.5$ mm
- ➢ distance between core and l.v. coil = 3.5 mm
- ➢ inside diameter of l.v. coil = $140+ (2 \times 3.5) = 147$ mm
- ➢ outside diameter of l.v. winding = $147 + (2 \times 8.5) = 164$ mm
- ➢ mean diameter of l.v. coil = $147 + 8.5= 155.5$ mm
- ➢ mean length of turn of l.v. coil $=\pi d= 155.5\times \pi = 488.27$ mm

Change Design and layout of H.V. winding

- The distance between L.V. and H.V. = 12 mm
- Inside diameter of h.v. = 164 + (12× 2) = 188 mm
- Now, Split h.v. winding in 4 coils each with turns = 2568/4 = 634
- The size of conductor = 1.25 mm diameter.
- With paper insulation on conductor, the diameter = (1.25 + 0.25) mm= 1.50 mm

- Choose 12 layers ; turns per layer = 634/10 = 64
- height of winding in each h.v. coil = 64× 1.5 =96 mm
- thickness of each coil = 10 × 1.5 = 15 mm
- outside diameter of h.v. coil = 188 + (2×15) = 218 mm
- mean diameter of h.v. coil = 188 + 15 = 203 mm
- mean length of turn =π×d=203× π = 637.42 mm
- height of h.v. coils in window = (96× 4) +8+8+8 =408 mm
- The space required between coils and core on either side is taken as 26 mm.
- The height of window required:= 408 + 24× 2 = 456 mm ; Which is acceptable

- **[N:B: window width=102 mm, height = 456 mm;]*****

Percentage Reactance

L.V. mean length of turn= 155.5× π = 488.27 mm
H.V. mean length of turn = 206× π = 646.84 mm

$$L_{mt} = \frac{488.27 + 637.42}{2} = 562.84mm$$

$$AT = 139 \times 54$$

$$mean\,height\text{ of coils} = \frac{392 + 408}{2} = 400mm$$

$$a = 12mm,\ \text{b1} = \text{width of h, v} = 22.5;\ \text{b2} = \text{width of l.v} = 17\text{mm}$$

$$\text{a} + \frac{\text{b}_1 + b_2}{3} = 12 + \frac{22.5 + 17}{3} = 25.16\,mm$$

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

$$= \frac{2\pi \times 50 \times 4\pi \times 10^{-7} \times 0.56284 \times 7506 \times 0.02516}{0.4 \times 4.5} = 0.04256\ p.u.$$

$$or;\ \ \%\,X = 2.32\%$$

PERCENTAGE OF IMPEDANCE

- percentage resistance
- % R =(Eq. Resistance / Base Resistance)

  $= (55.24) \div (11\times 10^3/3.03) \times 100\% = 1.52\%$

Here,

- % X = 2.32 %;
- % R = 1.52%

Therefore,

- Percentage impedance, $\%Z = \sqrt{(2.32^2 + 1.52^2)} \times 100\%$

  $= 2.77\ \%$

N.B: % Z is too low expectable limit, So change your dimension again

Again Change window dimension for modifiying % Z

$$\left.\begin{aligned} W_w &= 0.78\times140 = 109.2 \approx 110mm \\ L &= \frac{A_w}{W_w} = \frac{40779}{110} = 370.7 \approx 370mm \end{aligned}\right\} \text{And } A_w = 40{,}700\, mm^2$$

D= Distance between center of adjacent limb
= d+W_w

Choosing desire window width:

W_W= 0.78xd=0.78x140 = 110 mm
H ⇒ L = 370 mm
m_w = 12+5+14=31 ≅ 30mm
H_y =28 mm
D= 140x0.95+110 =243 mm

Height of window H = 370 mm;
Clearance to yoke=30 mm
Then, Height of window H = 370 + 30 × 2=430 mm;
Total width = (2 × 243) + 133 = mm=619 mm ;
Total height = 430 + 133+133 = 696 mm;

Where
W_w=width of window
H_w=Height of window
H_y= Height of the yoke
H=Overall height of frame
=H_w+2H_y
W=Overall width of frame
=2D+a

Design the layout of l.v. winding

- Number of turns in L.V= 54.
- Size of conductor : 2 strips of 4×7 mm , If, paper insulation of conductor=0.25 mm;
- With paper insulation for conductors,

$= (4+ 0.25)$ mm $\times$ $(7 + 0.25)$ mm; $=(4.25 \times 7.25)$ mm

$= 30.81$ mm^2

- Choosing 2 layers for l.v. winding,
- Turns per layer = 54 / 2 = 27
- Width of conductor 7.25 mm is taken along the winding,
- with 2 conductor sides 4.25 + 4.25 = 8.5 mm forming conductor per layer.
- For two layers, the dimension of conductors,
- width wise is 17mm and

- height of l.v. winding in window = $27\times7.25 = 195.75$ mm; say 196 mm;
- thickness of l.v. coil = $8.5\times 2 = 17$ mm
- distance between core and l.v. coil = 3.5 mm
- inside diameter of l.v. coil = $140+ (2 \times 3.5) = 147$ mm
- outside diameter of l.v. winding = $147 + (2 \times 17) = 181$ mm
- mean diameter of l.v. coil = 147 + 17= 164 mm
- mean length of turn of l.v. coil $=\pi d= 164\times \pi = 515$ mm

DESIGN AND LAYOUT OF H.V. WINDING

- The distance between L.V. and H.V. = 12 mm
- Inside diameter of h.v. = 181 + (12× 2) = 205 mm
- Now, Split h.v. winding in 4 coils each with turns = 2568/4 = 634
- The size of conductor = 1.25 mm diameter.
- With paper insulation on conductor, the diameter = (1.25 + 0.25) mm= 1.50 mm

- Choose 12 layers ; turns per layer = 634/12 = 54
- height of winding in each h.v. coil = 54× 1.5 =81 mm
- thickness of each coil = 12× 1.5 = 18 mm
- outside diameter of h.v. coil = 205 + (2×18) = 241 mm
- mean diameter of h.v. coil = 205 + 18 = 223 mm
- mean length of turn =π×d=223× π = 700.22 mm
- height of h.v. coils in window = (81× 4) +8+8+8 =348 mm
- The space required between coils and core on either side is taken as 30 mm.
- The height of window required:= 348 + 30× 2 = 408 mm ; Which is acceptable

- **[N:B: window width=110 mm, height = 430 mm;]*****

Percentage Reactance

L.V. mean length of turn= 164× π = 515 mm
H.V. mean length of turn = 223× π = 700.22 mm

$$L_{mt} = \frac{515+700.22}{2} = 607.61 mm$$

$$AT = 139 \times 54$$

$$mean\, height \text{ of coils} = \frac{196+348}{2} = 272 mm$$

$$a = 12 mm,\ \text{b1} = \text{width of h,v} = 22.5;\ \text{b2} = \text{width of l.v} = 17\text{mm}$$

$$\text{a} + \frac{\text{b}_1 + b_2}{3} = 12 + \frac{22.5+17}{3} = 25.16\, mm$$

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

$$= \frac{2\pi \times 50 \times 4\pi \times 10^{-7} \times 0.607 \times 7506 \times 0.02516}{0.272 \times 4.5} = 0.04256\, p.u.$$

$$or;\ \ \%\, X = 3.69\%$$

Percentage of IMPEDANCE

- percentage resistance
- % R =(Eq. Resistance / Base Resistance)

  $= (55.24) \div (11 \times 10^3/3.03) \times 100\% = 1.52\%$

Here,

- % X = 3.69 %;
- % R = 1.52%

Therefore,

- Percentage impedance, $\%Z = \sqrt{(3.69^2 + 1.52^2)} \times 100\%$

  $= 3.99\ \%$

N.B: This %Z is within expectable limit (3.5-4.5%)

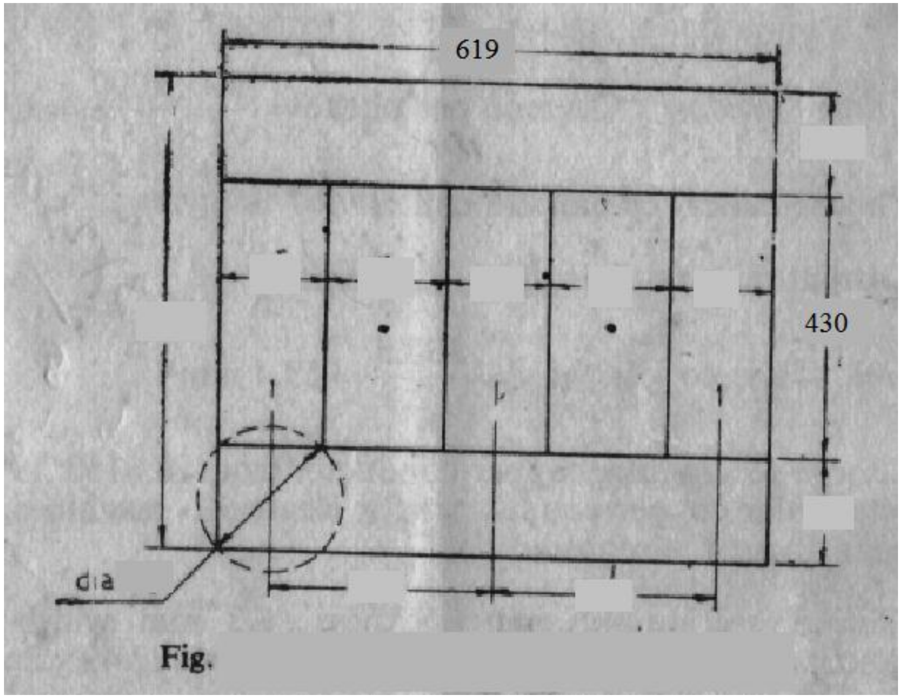
WEIGHT OF IRON IN CORE AND YOKE ASSEMBLY:

From the Figure, the volume of the core and yoke is given by:

$$= A_i \times \{ (619 \times 2) + (430 \times 3) \} \text{ mm}^3$$

$$= 12456 \times 2528 \text{ mm}^3 ;$$

$$= 31488768 \text{ mm}^3$$



WEIGHT OF IRON IN CORE AND YOKE ASSEMBLY…

Now, volume = 31488768 mm^3

Weight of iron = 7.85×1000 kg /m^3.

Weight of core and yoke

$= (31488768 \times 7.85) \div (1000 \times 1000) = 247$ kg

Core loss at $B_{max} = 1.63$ wb/ m^2 is 1.2 watts/kg (Fig. 2.2)

Core less in transformer $= 247 \times 1.2 \cong 296$ watts

WEIGHT OF IRON IN CORE AND YOKE ASSEMBLY…

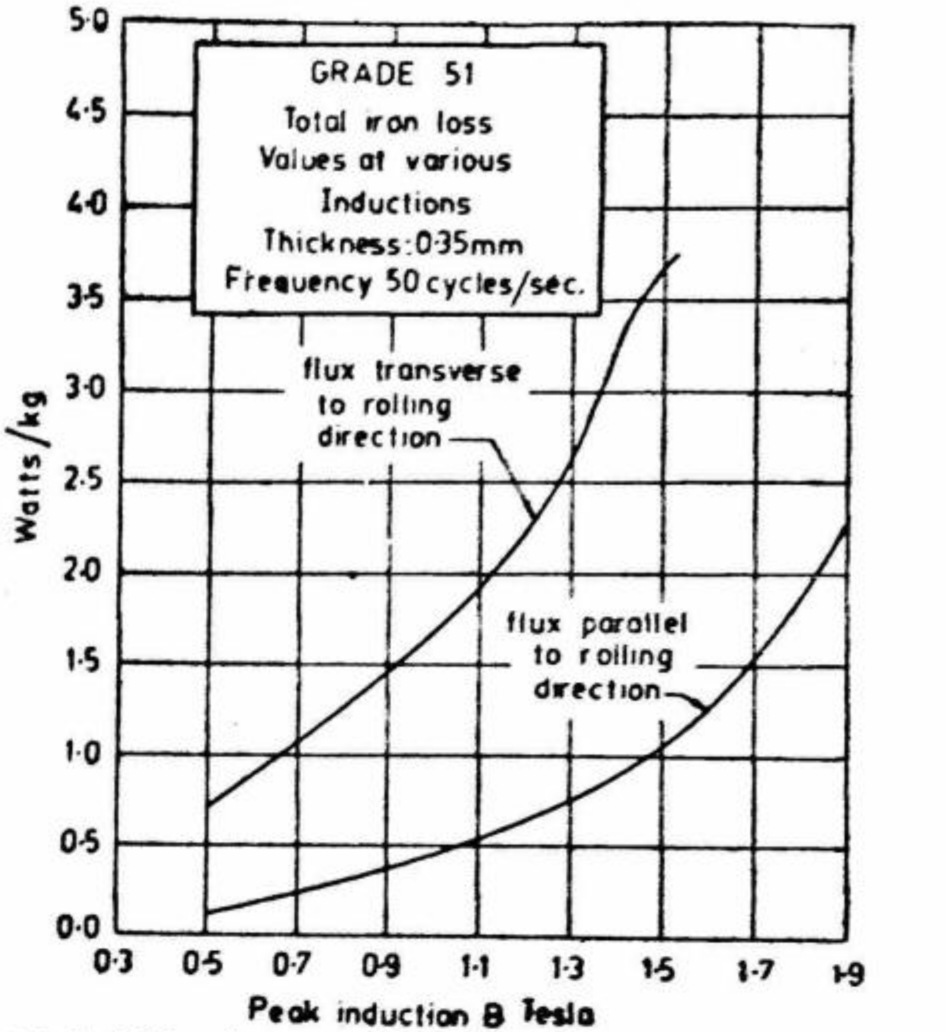


Fig. 2.2. Total iron loss watts/kg v/s peak density in Tesla (grade 51)

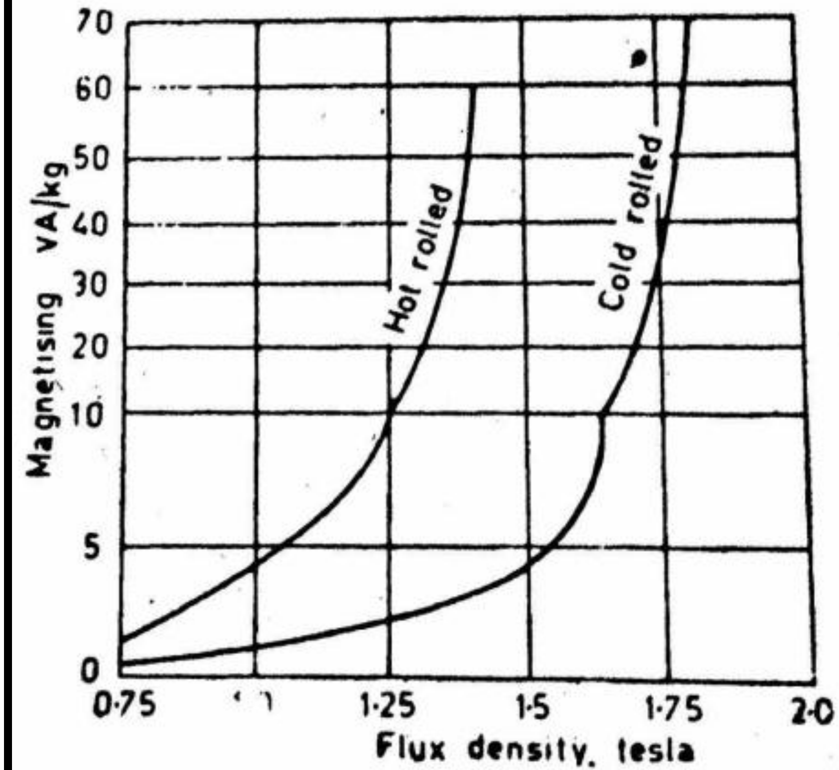


Fig. 4.10. VA/kg v/s B

MAGNETIZING VOLT AMPERES

- **Magnetizing volt amperes:**

For B_{max} = 1.63 wb/m^2, VA / kg from the curve (Fig. 4.10) is 10 VA/kg

Magnetizing volt amperes = 247× 10 VA = 2470 VA

- **Weight of L.V. winding :**

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

Number of turns = 54 & Area of L.V. conductor, a_2 = 56 mm^2

Mean length of turn = 515 mm

Weight of l.v. winding (per limb)

$= (8.89 \times 56 \times 515 \times 54) \div (1000 \times 1000) = 13.84$ kg

WEIGHT OF IRON IN CORE AND YOKE ASSEMBLY

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

Number of turns = 2568; (normal 2445) ; $a_1 = 1.21\ mm^2$;

Mean length of turn = 700.22 mm

Weight of 4 coils (one limb)

$= (8.89 \times 1.21 \times 700.22 \times 2568) \div (1000 \times 1000)$ kg

= 19.34 kg ; for all turns

For normal turns, weight of the coils (one limb)

$= (8.89 \times 1.29 \times 700.22 \times 2445) \div (1000 \times 1000)$ kg

= 18.41 kg

TOTAL WEIGHT OF COPPER IN TRANSFORMER

- **Total weight of copper in transformer:**

Total weight

$$= 3\ (L.V + H.V.)$$

$$= 3\ (13.84 + 18.41)\ kg$$

$$= 96.75\ kg$$

Copper loss and Load loss at 75° C

- **Copper loss and Load loss at 75° C :**

H.V. current per phase = 3.03 A

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

$= 3 \times 3.03^2 \times 55.24$

$= 1521.76$ W

Let, stray load loss about 7%,

Then, Load Loss (at 75^0C) = 1521.76 ×1 .07 = 1628 watts

Iron loss = 296 watts

Hence, Total Loss = (296 + 1628)

= 1924 watts

- **Calculation of performance:**
- Efficiency on full load at unity power factor :

Output = 100× 1000 watts ; (100 kVA Transformer)

Efficiency = Output / Input

= 100 ×1000/(100 × 1000+1924) × 100%

= 98.11%

CALCULATION OF PERFORMANCE

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

Core loss = 296 watts;

Load loss on 3/4 load $= 1628\times (3/4)^2 = 916$ Watt;

Total loss = 296 + 916 = 1212 watts

Efficiency on 3/4th of full load

$$= 75000/(75000+1212) \times 100\%$$

$$= 98.4\%$$

CALCULATION OF PERFORMANCE

- Efficiency on ½ of full load at unity power factor:

Core loss = 296 watts;

Load loss on 1/2 load = $1628 \times (1/2)^2 = 407$ W

Total loss = (296 + 407)

= 703 watts

Efficiency on 1/2 of full load

$= 50000/(50000+703) \times 100\%$

= 98.61 %

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

% R = 1.52%, % X = 3.69%

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

or, $(1.0 + 0.0152)^2 + (0.0369)^2 = 1.031 = E^2$

or, $E = 1.015$

Regulation = 1.015 – 1.0

= 0.015 p.u.

= 1. 5%

- **Regulation on full load at 0.8 power factor lagging**

$= [IR \cos \varphi + IX \sin \varphi]$ %

$= [1.52\times 0.8 + 3.69\times 0.6]$ % = 3.43 %

- **Core loss current, magnetizing current:**

Core loss = 296 watts.

core loss current, $I_c = (296) \div (3 \times 11000)$

$= 0.0089$ A

Magnetizing VA = 2470 ;

magnetizing current, $I_m = (2470) \div (3 \times 11000)$

$= 0.0748$ A

NO-LOAD CURRENT

- **No load current:**

No load current per phase , $I_o = \sqrt{(I_c^2 + I_m^2)}$

$= \sqrt{(0.0748^2 + 0.0089^2)}$

$= 0.0753$ A

Current per phase = 3.03 A

Hence, No load current is (0.0753 ÷ 3.03) × 100 %

= 2.48% of the full load current


Self-Study

Assignment: 13 Batch

Section B:

Design….

6.6kV/210V, (last 3 Digit of Student ID+25) kVA

For example, if your student ID is 1302067

then (067+25) = 92 kVA


thank
you!