Chapter III

DESIGN OF A HIGH VOLTAGE TESTING TRANSFORMER

OBJECTIVES:

Design a transformer to meet the following specifications

Indoor, self-cooled, oil-immersed type, one terminal of the high voltage winding is solidly grounded to tank.

Output in kilovolt-amperes	5	KVA
Rated Primary (Low-tension) voltage	220	volts
Rated Secondary (High-tension) voltage	100,000	volts
Rated Primary (Low-tension) currents	22.7	amperes
Rated Secondary (High-tension) currents	0.05	amperes
Rated Frequency	50	Hz.

The flux density in the core (B) can be chosen equal to 1.4 Weber per sq.m.

From the core loss curve of RG-8H (0.30mm. thickness) silicon steel Fig. 4.1

The loss per kilogram for this density w_c = 0.74 Watts, if the additional losses are taken equal to 12.0% of the fundamental frequency losses.

The core losses per kilogram, $w_c = 0.74 \times 1.12 = 0.83$ Watts

For an average current density, $A = 200$ amperes per sq.cm.

The copper losses per kilogram, $w_k = 2.37\ A^2\ k_5 \times 10^{-4}$

$$= 2.37\ (200)^2 \times 1.1 \times 10^{-4}$$

$$= 10.43 \text{ Watts}$$

The ratio of core weight to copper weight

$$\frac{G_c}{G_k} = \frac{w_k}{w_c} \times \frac{W_c}{W_k}$$

$$= \frac{10.43}{0.83} \times 1 = 12.57$$

The output constant is taken equal to 0.45 and the net section area of the core

$$A_c = C \sqrt{\frac{KVA \times \frac{G_c}{G_k} \times 10^{11}}{BAf}}$$

$$= 0.45 \sqrt{\frac{5 \times 12.57 \times 10^{11}}{14 \times 10^3 \times 200 \times 50}}$$

$$= 95.4 \text{ sq cm.}$$

The cruciform-shaped core section shown in Fig. 3.1 will be used for this transformer. The diameter of the core

$$D = \sqrt{\frac{A_c \times 4}{\pi f_{cs}}}$$

$$= \sqrt{\frac{95.4 \times 4}{3.14 \times 0.97}}$$

$$= 11.2 \text{ use } 11.7 \text{ cm.}$$

The dimensions of the core section are shown in Fig. 3.1

The total flux for a density of 14 kilo-lines per sq.cm.

$$\phi = A_c B$$

$$= 94.0 \times 14$$

$$= 1316.0 \text{ kilo-lines}$$

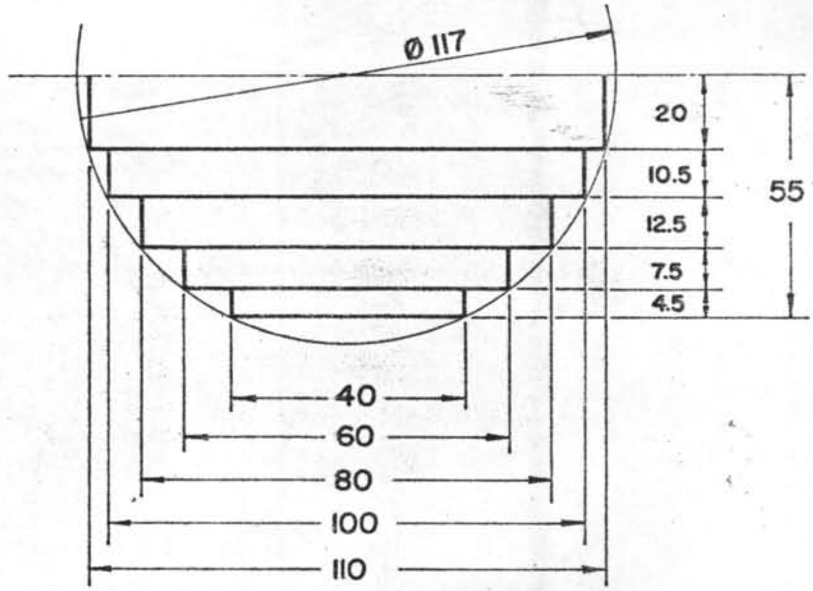

Fig. 3.1 Core area Ø 117 (millimetres)

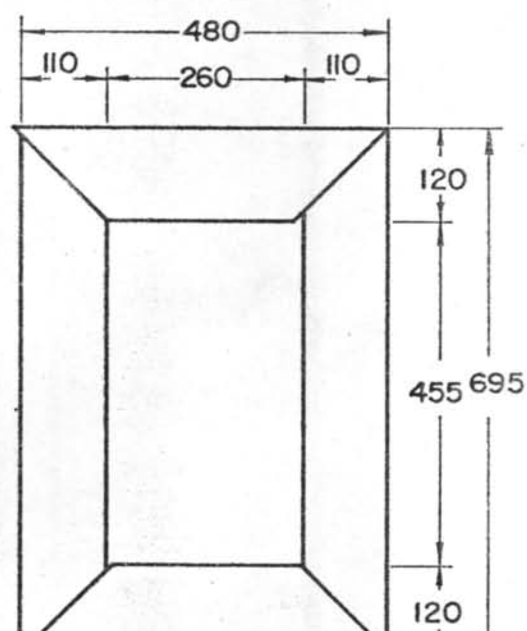

Fig. 3.2 Core dimensions, Window opening, Mean magnatic path in millimetres

The number of turns for high-voltage winding

$$t_h = \frac{E_h \times 10^8}{4.44\ f\ \phi}$$

$$= \frac{100{,}000 \times 10^8}{4.44 \times 50 \times 1376.0 \times 10^3}$$

$$= 34229 \text{ turns}$$

$$\text{use } t_h = 34546 \text{ turns}$$

The number of turns for low-voltage winding

$$t_l = \frac{E_l}{E_h} \times t_n$$

$$= \frac{220 \times 34546}{100{,}000} = 76 \text{ turns}$$

The full-load current in the two windings

$$I_h = \frac{KVA \times 10^3}{E_h} = \frac{5 \times 10^3}{100{,}000}$$

$$= 0.05 \text{ amperes}$$

$$I_l = \frac{KVA \times 10^3}{E_l} = \frac{5 \times 10^3}{220}$$

$$= 22.7 \text{ amperes}$$

For average current density assumed, the section area of the conductors for high-voltage and low-voltage windings.

$$S_{ch} = \frac{I_h}{A} = \frac{0.05}{200}$$

$$= 0.00025 \text{ sq.cm.}$$

$$S_{ch} = \frac{I_l}{A} = \frac{22.7}{200}$$

$$= 0.11364 \text{ sq.cm.}$$

The area of the window opening

$$h_w w_w = \frac{2S_{ch}t_h}{f_s}$$

where f_s [1] =space factor $= \frac{10}{30 + KV}$

$$= \frac{10}{30 + 100} = 0.07692$$

Reduce 25% of f_s because of small transformer

$$f_s = 0.07692 \times 0.75$$

$$= 0.05769$$

$$h_w w_w = \frac{2 \times 0.00025 \times 34{,}546}{0.05769}$$

$$= 299.41 \text{ sq.cm.}$$

For ratio of window height to window width equal to 3.0 the dimensions of the window are:

$$h_w = \sqrt{3.0 \times 299.41}$$

$$= 29.9 \text{ cm.; use } 30.0 \text{ cm.}$$

$$w_w = \frac{30.0}{3} = 10.0 \text{ cm.}$$

The length of the yoke; $l_y = 10.0 + (2x11.0) = 32.0$ cm.

The total weight of the core, $G_c = 2(l_y+h_w)A_c x D_c 10^{-3}$

D_c = The volume density of RG-8H steel

= 7.65 grams per cu.cm.

$$G_c = 2(32.0+30.0)94.0x7.65x10^{-3}$$

$$= 89.17 \text{ kg.}$$

The length of the average mean-turn for the windings

$$L_{av} = \pi \left(D + \frac{w_w - \beta}{2}\right)$$

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1. Alfred Still and Charles S Siskind, Electrical Machine Design (New York: McGraw-Hill, Inc., 1954) p. 348

The clearance, β between the two coils in the window opening should be approximately 7.0 cm.

$$L_{av} = \pi\,(11.7 + \frac{10.0 - 7.0}{2})$$

$$= 41.45 \text{ cm.}$$

The approximate total copper weight

$$G_k = 2t_h S_{ch} L_{av} D_k \times 10^{-3}$$

$$D_k = \text{copper wire density} = 8.87 \text{ gm. per cu. cm.}$$

then $$G_k = 2x34546x0.00025x41.45x8.87x10^{-3}$$

$$= 6.35 \text{ kg.}$$

The approximate ratio of core weight to copper weight

$$\frac{G_c}{G_k} = \frac{89.17}{6.35} = 14.0$$

Design of Windings

Low-voltage winding

A rectangular cross-section copper magnet wire with TKP Insulation (Triple kraft paper) is selected from the copper wire table. The dimensions of the conductor are;

Bare	7.0 x 1.5 mm.
Insulated	7.6 x 2.1 mm.
Arear	10.017 sq. mm.

The number of turns per core leg $= \frac{76}{2} = 38$ turns.

The windings are layer-wound type, with 2 layers per coil and 19 turns for each layer. For layer-wound coil, the space of the one turn must be used for the start of the windings.

The total height of the low-voltage coils is then,

$$= 0.76 \times 20 = 15.2 \text{ cm}$$

The voltage per turn $= \dfrac{220}{76} = 2.89$ volts

The maximun voltage between layer $= 2.89 \times 2 \times 19 = 109.82$ volts

The pressphane (kraft paper) insulation 0.13 mm thick will be placed between layers of the low-voltage coils

The width of each low-voltage coil is then,

$$d_1 = (2 \times 0.21) + 0.013 = 0.433 \text{ cm.}$$

$$\text{use } d_1 = 0.45 \text{ cm.}$$

High-Voltage Windings

A No. 37 SWG polyvinyl formal round copper magnet wire is selected from the wire table and the dimensions of the conductor are,

The nominal diameter of bare conductor = 0.1727 mm.

The nominal diameter of insulated conductor = 0.214 mm.

The cross-section area of bare conductor = 0.02348 sq.mm.

The number of turns per core leg $= \dfrac{34546}{2}$

= 17273 turns

Disk-type coils will be used for the high voltage winding, with 4 coils per core leg connected in series. The number of layers per coil are 40, which consists of 2 layers of 69 turns and 38 layers of 110 turns.

The voltage per turn $= \dfrac{100{,}000}{34546} = 2.89$ volts

The maximum voltage between layers $= 2.89 \times 2 \times 110 = 635.8$ volts

3 layers of pressphane insulation 0.13 mm. thick will be placed between layers of windings in order to withstand induced voltage test and other

abnormal volta ge concentration.

The width of each high voltage coil is then,

$$d_h = 3.0+(40x0.214)+(40x3x0.13)$$

$$= 27.16 \text{ mm.}$$

$$\text{use } d_h = 28 \text{ mm.}$$

The width of each coil in the direction of window height

$$= (110x0.214)+(2x10.0)$$

$$= 43.54 \text{ mm. use } 44.0 \text{ mm.}$$

The insulations and oil ducts between coils are shown in Fig. 3.4 The total height of the high voltage coil is then,

$$h = (4x44.0)+(3x3.2)+(5x3.2)+(3x3.2)$$

$$= 211.1 \text{ mm.}$$

$$\text{use } h = 215.0 \text{ mm.}$$

The space at each end of the winding, which is required for insulation and supporting collars should be 12.0 cm.

The height of the window is then,

$$h_w = (2x120)+215$$

$$= 455 \text{ mm.}$$

The insulations and oil ducts between the high voltage and low voltage winding are shown in Fig 3.5.

The total thickness of the windings

$$= \frac{1}{2}(11.7-11.0)+0.3+0.45+4.8+2.8$$

$$= 8.7 \text{ cm.}$$

The clearance between the high voltage coils in the window opening should be 8.0 cm.

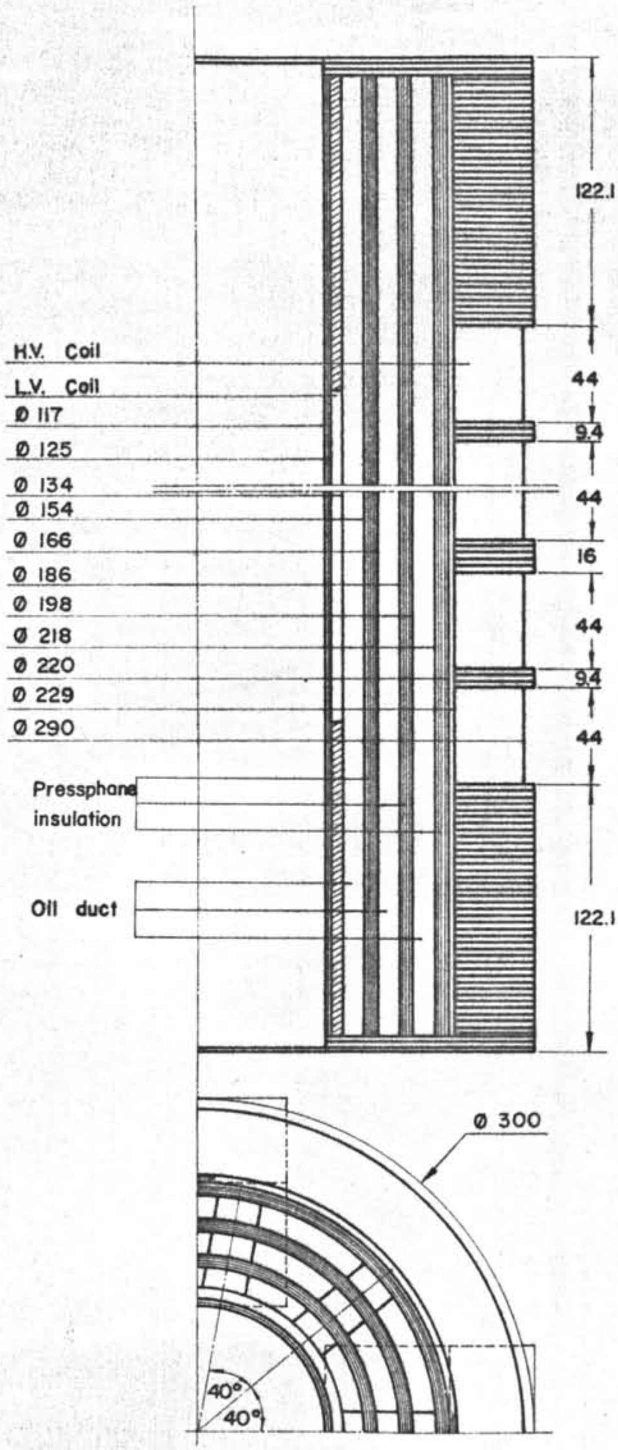

Fig. 3.3 Crossection of L.V. and H.V. coil (millimetres)

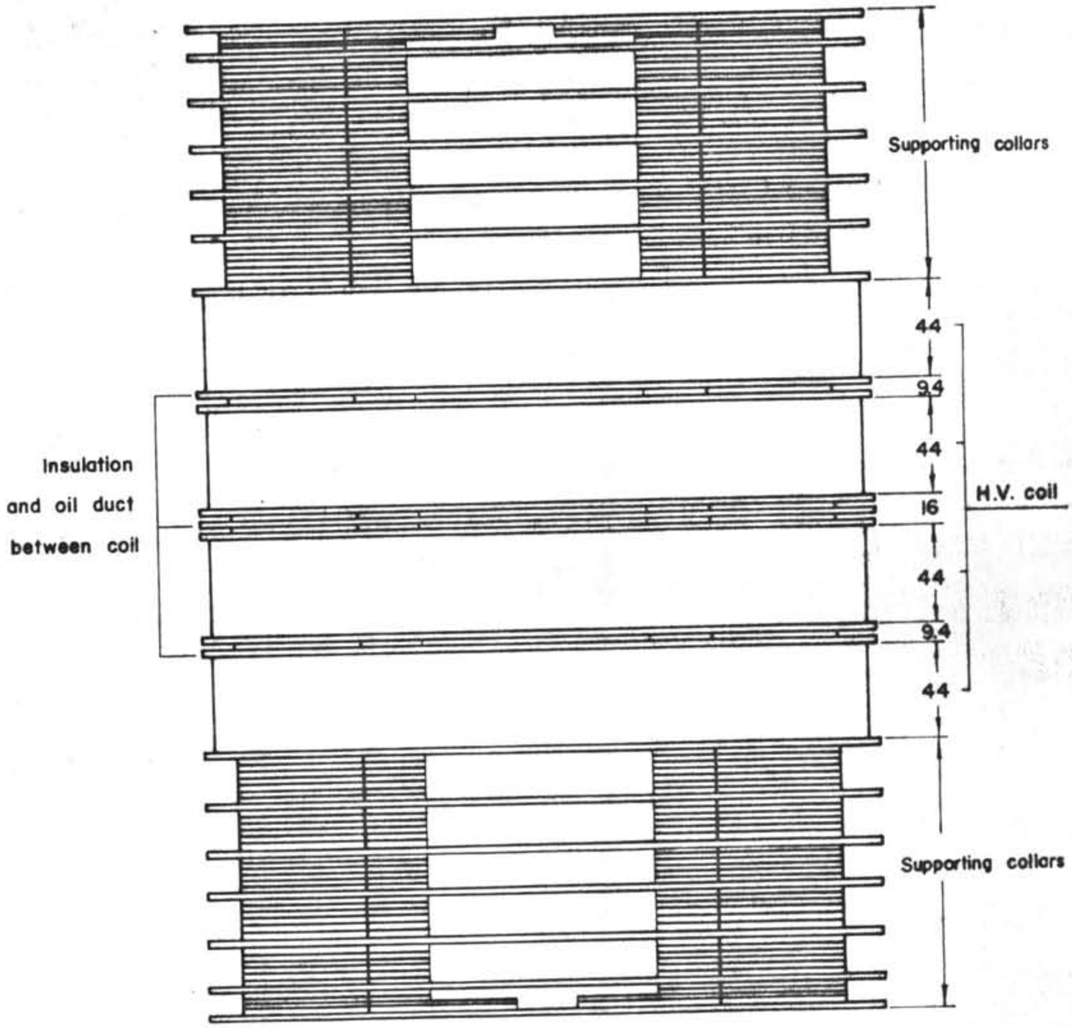

Fig. 3.4 H.V. Coil (millimetres)

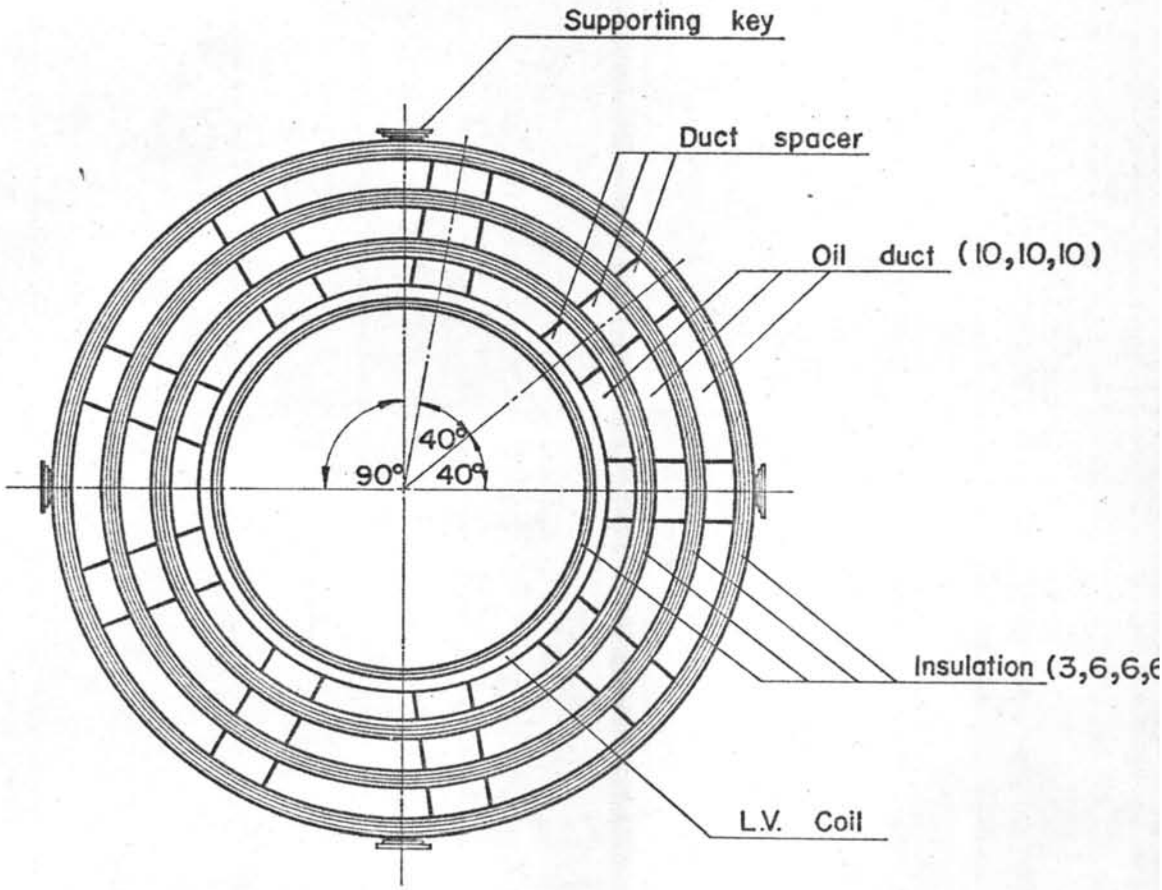

Fig. 3.5 L.V. Coil, insulation and oil duct (millimetres)

The width of the window is then,

$$w_w = (2x8.7) + 8.0$$

$$= 25.4 \text{ cm.}$$

$$\text{use} \quad w_w = 26.0 \text{ cm.}$$

The dimensions of the window opening are then,

$$h_w = 45.5 \text{ cm;}$$

$$\text{and} \quad w_w = 26.0 \text{ cm.}$$

Since the dimensions of the window have been changed from the value first determined, it will be necessary to recalculate the weight of core.

The length of yoke; $= 26.0+2\times11.0 = 48.0$ cm.

The weight of yoke; $= 2\times48.0\times94\times7.65\times10^{-3}$

$= 69.0$ kg.

The weight of core leg $= 2\times45.5\times94\times7.65\times10^{-3}$

$= 65.4$ kg.

The total weight of steel core; $G_c = 69.0+65.4 = 134.4$ kg.

The current density in the low-voltage winding

$$A_1 = \frac{I_1}{S_{c1}} = \frac{22.7}{0.10017}$$

$$= 226.88 \text{ ampere per sq.cm.}$$

and in the high-voltage winding

$$A_h = \frac{I_h}{S_{ch}} = \frac{0.05}{0.0002348}$$

$$= 212.95 \text{ ampere per sq.cm.}$$

The length of the mean-turn for the low-voltage winding

$$L_1 = 2\pi\left(\frac{D}{2} + 0.30 + \frac{d_1}{2}\right)$$

$$= 2\pi\left(\frac{11.7}{2} + 0.30 + \frac{0.45}{2}\right)$$

$$= 40.0 \text{ cm.}$$

and for the high-voltage winding

$$L_h = 2\pi\left(\frac{D}{2} + 0.30 + d_1 + d + \frac{d_h}{2}\right)$$

$$= 2\pi\left(\frac{11.7}{2} + 0.30 + 0.45 + 4.8 + \frac{2.8}{2}\right)$$

$$= 80.4 \text{ cm.}$$

The low voltage winding copper weight

$$G_1 = t_1 S_{ch} L_1 \times 8.87 \times 10^{-3}$$
$$= 76 x 0.10017 x 40.0 x 8.87 x 10^{-3}$$
$$= 2.70 \text{ kg.}$$

and the high voltage winding copper weight

$$G_h = t_h S_{ch} L_h \times 8.87 \times 10^{-3}$$
$$= 34546 x 0.0002348 x 80.4 x 8.87 x 10^{-3}$$
$$= 5.79 \text{ kg.}$$

The total copper weight

$$G_k = G_1 + G_h$$
$$= 2.70 + 5.79 = 8.49 \text{ kg.}$$

The ratio of core weight to copper weight

$$\frac{G_c}{G_k} = \frac{134.4}{8.49} = 15.8$$

From the core loss curve for RG-8H (0.30 mm. thick) the loss per kilogram for a density of 14 kilolines per sq.cm.

$$w_c = 0.74 \times 1.12$$
$$= 0.83 \text{ watts/kg.}$$

The total core loss

$$W_c = 0.83 \times 134.4 = 111.6 \text{ watts}$$

The I^2R loss plus stray load loss in low-voltage winding at 75°C

$$W_1 = 2.37 A^2{}_1 G_1 \times 1.1 \times 10^{-4}$$
$$= 2.37(226.88)^2 x 2.7 x 1.1 x 10^{-4}$$
$$= 36.2 \text{ watts}$$

and in high voltage winding at 75°C

$$W_h = 2.37\ A_h^2\ G_h \times 1.1 \times 10^{-4}$$

$$= 2.37(212.95)^2 x5.79x1.1x10^{-4}$$

$$= 68.5 \text{ watts}$$

The total copper loss

$$W_k = W_1 + W_h$$

$$= 36.2 + 68.5 = 104.7 \text{ watts}$$

The ratio of losses

$$\frac{W_c}{W_k} = \frac{111.6}{104.7} = 1.07$$

The resistance of the low voltage winding at 75°C

$$R_1 = \frac{W_1}{I_1^2} = \frac{36.2}{(22.7)^2}$$

$$= 0.0703 \text{ ohms}$$

and of high voltage winding at 75°C

$$R_h = \frac{W_h}{I_h^2} = \frac{68.5}{(0.05)^2}$$

$$= 27,400 \text{ Ohms}$$

The total resistance in terms of the high voltage winding

$$R_t = \frac{W_k}{I_h^2} = \frac{104.7}{(0.05)^2}$$

$$= 41,880 \text{ Ohms}$$

The percent resistance drop

$$P_r = \frac{I_h\ R_t}{E_h} \times 100\ \%$$

$$= \frac{0.05 \times 41,880}{100,000} \times 100\ \%$$

$$= 2.09\ \%$$

The percent reactance drop (low-voltage winding are connected in series)

$$P_x = \frac{2 \times 8.47\ ft_h^2\ I_h}{hE_h \times 10^6} \left(\frac{d_h + d_l}{3} + d\right) \frac{L_h + L_l}{2}$$

From Fig. 3.3

$$d_h = 2.8 \text{ cm.}$$

$$d_l = 0.45 \text{ cm.}$$

$$d = 4.8 \text{ cm.}$$

$$h = 21.5 \text{ cm.}$$

$$P_x = \frac{2 \times 8.47 \times 50 \times (17273)^2 \times 0.05}{21.5 \times 100{,}000 \times 10^6} \left(\frac{2.8 + 0.45}{3} + 4.8\right) \times$$

$$\times \frac{40.0 + 80.4}{2}$$

$$= \frac{2 \times 8.47 \times 50 \times (17273)^2 \times 0.05 \times 5.88 \times 60.2}{21.5 \times 100{,}000 \times 10^6}$$

$$= 2.08\ \%$$

The percent impedance drop

$$P_z = \sqrt{P_x^2 + P_r^2}$$

$$= \sqrt{2.08^2 + 2.09^2}$$

$$= 2.95\ \%$$

The sustained short circuit current for normal primary voltage

$$I' = \frac{I_h \times 100}{P_z}$$

$$= \frac{0.05 \times 100}{2.95}$$

$$= 1.69 \text{ amperes}$$

The percent regulation for 100% power factor load

$$= P_r + \frac{P_x^2}{200}$$

$$= 2.09 + \frac{2.08^2}{200}$$

$$= 2.11\ \%$$

and for 80% power factor load, the percent regulation

$$= P_r \cos\theta + P_x \sin\theta + \frac{(P_x \cos\theta + P_r \sin\theta)^2}{200}$$

$$= (2.09 \times 0.8) + (2.08 \times 0.6) + \frac{(2.08 \times 0.8 + 2.09 \times 0.6)^2}{200}$$

$$= 2.96\ \%$$

The mean-length of the flux path (L_{av}) is shown by the dotted line in Fig. 3.2

$$L_{av} = 2(h_w + h_y) + 2(w_w + b)$$

$$= 2(45.5 + 42.0) + 2(26.0 + 11.0)$$

$$= 189 \text{ cm.}$$

From the magnetizing curve of RG-8H (0.30 mm. thick) Fig 4.2

The ampere-turn per metre for a density of 14 kilo-lines per sq.m.

$$at = 20.5 \text{ ampere-turn per metre}$$

Total ampere-turn necessary to maintain the flux in the iron path of the magnetic circuit

$$= at \times L_{av} = 20.5 \times 1.89$$

$$= 38.75 \text{ ampere-turn}$$

The ampere-turn for 4 joint at a density of 14 kilo-lines per sq.cm. is about 120 times the ampere-turn per cm.

The ampere-turn for 4 joint $= 0.205 \times 120 = 24.6$ ampere-turn

The total ampere-turn (AT) $= 38.75 + 24.6 = 63.35$ ampere-turn

The magnetizing current, $I_m = \dfrac{AT}{\sqrt{2}\, t_h}$

$$= \frac{63.35}{2 \times 34546}$$

$$= 1.30 \text{ mA}$$

The inphase component of the no-load current

$$I_w = \frac{W_c}{E_h}$$

$$= \frac{111.6}{100{,}000}$$

$$= 0.001116 \text{ ampere}$$

The exciting current $= \sqrt{I_m^2 + I_w^2}$

$$= \sqrt{(1.30)^2 + (1.116)^2}$$

$$= 1.595 \text{ mA}$$

The total radiating surface of the transformer winding and core is calculated as follows:

Core legs : $2 \left[4 \times 40 + 2\,(20 + 20 + 20 + 10) + 4\,(10.5 + 12.5 + 7.5 + 4.5) \right] 455$

$= 418600$ sq.mm. $= 4186$ sq.cm.

Yokes : $2 \left[2 \times 40 + 2\,(10.5 + 12.5 + 12.0) + 2\,(10 + 20 + 20) \right] 490$

$= 245000$ sq.mm. $= 2450$ sq.cm.

Low-voltage winding : $2 \times 40 \times 15.2 \times 2 = 2432$ sq.cm.

High-voltage winding : $2 \times 4 \times 4.4 \times 80.4 \times 2 = 5660.16$ sq.cm.

Total radiating surface $= 14{,}728.16$ sq cm.

and the surface per watt loss ; $\frac{S}{W} = \frac{14{,}728.16}{216.13}$

$$= 68.09$$

The plain sheet-steel with 0.3175 cm. thickness are used for the tank. Fig. 5.9 shows the shape of tank section.

The cross-section area of the tank = 90×58.5 = 5265 sq.cm.

The height of the tank = 110 cm.

The depth of oil in the tank = 90 cm.

The volume of oil in the tank = 5265×90 = 473,850 cu.cm.

The volume of the transformer can be calculated approximately from the weight of the active materials. The insulation, core clamp, coil supports, etc., occupy only a small percent of the space required for the active material

The approximate volume of the transformer

$$= \frac{134.4}{7.65 \times 10^{-3}} + \frac{8.49}{8.87 \times 10^{-3}}$$

= 18,530 cu.cm.

The volume of oil required = 473,850 - 18,530

= 455,320 cu.cm.

= 455.32 litres

The density of oil is 0.9 kg./litre

The weight of oil = 0.9×455.32 = 409.79 kgs.

TRANSFORMER DESIGN SHEET

Kva, 5 Phase, single Cycles, 50	volts	H.V. 100,000	
		L.V. 220	
Type of cooling, natural-oil-cooled	amperes	H.V. 0.05	
		L.V. 22.7	

Core		Magnetizing current, mA		1.30
Sheet steel, RG-8H,	0.30 mm.	Core loss current, mA		1.116
Output constant	0.45	Exciting current, mA		1.595
Core leg:		Percent:		
Area, sq.cm.	94.0	Resistance		2.09
Diameter, cm.	11.7	Reactance		2.08
Dimensions,	see Fig. 3.1	Impedance		2.95
Density, line/sq.cm.	14,000	Power factor	80	100
Weights, kg.	65.4	Regulation	2.96	2.11
Yoke:		Losses:		
Area, sq.cm.	94	Total core, watts		111.6
Dimensions,	see Fig. 3.1	Stray load, watts		36.2
Weights, kg.	69.0	Total copper, watts		104.7
Copper Space Factor	0.05769	Square cm. per watt		68.09
Window dimensions, cm.		Ratio of losses		1.07
h_w = 45.5, W_w =	26.0	Ratio of weight		15.8
Lamination factor,	0.97			
		Tank		
Core and Winding		Type of tank, Plain sheet-steel		
Mean length of flux path, cm.	189			0.3175 cm. thick
Total ampere-turn	69.5	Total wetted surface, sq.cm.		32670

Depth of oil, cm.	90	Litres of oil,	465.32
		Weights of oil, kg.	409.79

Windings	High voltage	Low voltage
Type of windings	Disk-coils	Layer-wound
Conductor:		
Size, copper wire	No.37 SWG, round	7.0 x 1.5 mm., rectangular
Cross-section area, sq.mm.	0.02348	10.017
Current density, amp/sq.cm.	212.95	226.88
No. of turns	34546	76
Coils:		
Total number	8	2
Per core leg	4	1
Turns:		
Per coil	4318	38
Per layer, number-turn	1-69, 38-110, 1-69	19
Coils:		
Connection	series	series
Dimensions, cm.	2.8 x 4.4	0.45 x 15.2
Ducts, number and size, cm.	3-1.0	-
Insulation:		
Layer, cm.	3-0.013	1-0.013
Core and Coils, cm.	-	0.30
H.V. and L.V., cm.	3-0.6	-
Voltage per turn, volts	2.89	2.89

Max. voltage B.W.T. layers, volts	635.8	109.82
Length of mean turn, cm.	80.4	40.0
Copper:		
Weight, kgs	5.79	2.70
Loss, watts	68.5	36.2
Resistance at 75°C, ohms	27400	0.0703