Chapter 19

High Voltage Transformer for DC Electron Accelerators

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This chapter covers the design, development and analysis of High Voltage and High Frequency Transformer for DC Accelerator application. The input and output of the transformer (Fig. 19.1) are high power, high frequency sinusoidal inverter and high power, high voltage dc accelerator based on symmetrical Cockcroft-Walton scheme respectively. The specifications of the transformer are given in Table 19.1.

Table 19.1: Specification of 125 kVA, HV & HF Transformer.

Parameter	**Value**
Power rating	125 kVA
Input Voltage	500 V_P
Output voltage	45kV_P-0-45kV_P
Turns Ratio	180
Frequency	10 ± 0.5 kHz
Phase	single
Cooling	ONWF

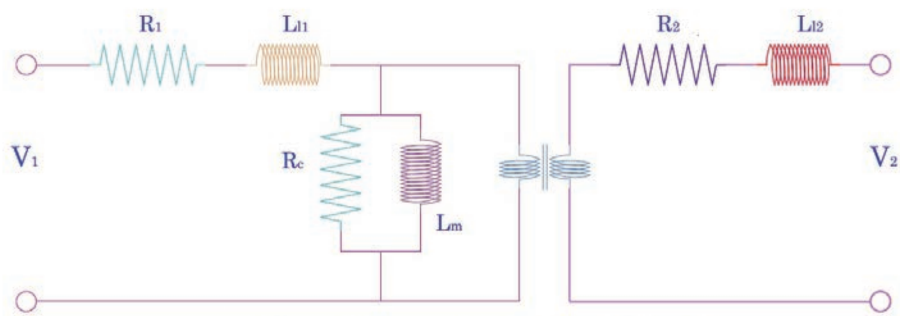

Figure 19.1: The transformer equivalent circuit.

19.1 Design

The input power of the transformer is coming from the high frequency inverter and the output load is symmetrical Cockcroft-Walton multiplier. This Centre-tapped HV and HF transformer design is similar to full wave center-tapped secondary rectifier transformer design scheme as shown in Fig. 19.2(a).

19.1.1 125 kVA Transformer Design Steps

The Apparent power, P_t for full wave Center-Tapped Secondary and area product, A_p are

$$P_t = P_o\left(\frac{1}{\eta} + \sqrt{2}\right) = 100\ kW\left(\frac{1}{0.98} + 1.414\right) = 243.4\ kW$$

and

$$A_p = \frac{P_t \times 10^4}{kB_m f k_u k_j} = \frac{243400 \times 10^4}{4.44 \times 0.2 \times 10\ kHz \times 0.03 \times 200} = 45,683.2\ cm^4$$

Area product is the product of window area and cross-section area of core. The following steps and tables are given below to calculate the required parameters and select appropriate materials for HV & HF transformer.

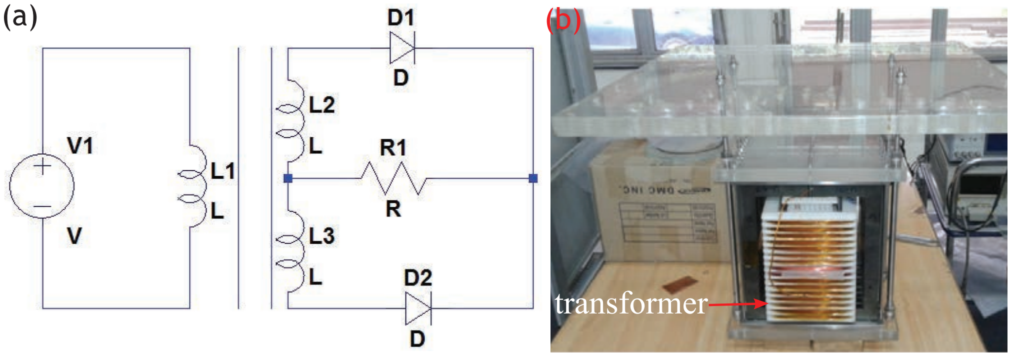

Figure 19.2: (a) Full wave center-tapped secondary rectifier transformer scheme, and (b) Prototype of assembly view of transformer.

1) **Turn Ratio**

We know that

$$V_{p(rms)} = 4.44 N_p A f B$$

where $V_{p(rms)}$ is primary voltage, N_p is primary number of turns, A is the cross-section area of the core, f is the frequency and B is the magnetic flux density. Therefore,

$$N_p = \frac{353.5\ V}{4.44 \times 100.8\ cm^2\ \times 10\ kHz \times 0.2\ T} = 3.9\ \sim\ 4$$

Secondary turn,

$$N_s \text{ is } 4\ \times 180 = 720.$$

2) **Core Selection**

24 no. of UIU core combination has been selected. The core cross-section area, window area and weight are 134.4 cm^2, 176.4 cm^2 and 45.3 kg respectively. The other important, core loss is 665.3 W.

3) **Primary winding cross-section**

The current density is 4 A/mm^2. The wire cross-section for 400 A is 100 mm^2 and the diameter of the conductor is 11.28 mm. The diameter and cross-section area of SWG 0 is 8.23 mm and 53.17 mm^2 therefore 2 No. of SWG 0 wire can be used. The skin depth at 10 kHz is 0.65 mm and therefore effective diameter of the conductor is 1.3 mm. Therefore, 86 number of SWG 18 can be used for 100 mm^2. The primary winding loss is 8.4 watt. Litz wire is a good alternative and it can also be used in the primary winding.

4) **Secondary winding**

The secondary voltage, current and turn are 90 kV_P, 1.88 A_{rms} and 720 respectively. There are 10 sections in the HV winding, 8 layers in each section and 9 turn in each layer therefore the per turn, per layer and each section voltage of secondary winding are 125 V, 1.125 kV and 9 kV respectively. The SWG 14 is required in HV secondary winding. The max electric field and winding loss of the secondary are 70.7 kV/cm and 156 W respectively.

5) **Material selection**

Insulating media should have high dielectric strength and high thermal stability. The following material has been listed in Table 19.2.

Table 19.2: Magnetic characteristics (per set).

Parameter	UU 126/182/20	UI 126/119/20	unit
$\sum$ l/A	0.86	0.63	mm^{-1}
l_e	480	354	mm
A_e	560	560	mm^2
A_{min}	560	560	mm^2
V_e	269000	198000	mm^3
m	1300	950	g/set

19.1.2 Core Selection

Variety of cores are available in the market for transformer e.g., silicon steel, Metglas, Ferrites, etc. The selection criteria of magnetic core for transformer are the lowest core loss at operating magnetic flux density and frequency and highest window length in the available cores. The highest window length is required for providing the HV insulation between windings and also gap insulation is required between HV winding and core. The silicon steel is the most preferred core in 50 Hz applications but for high frequency application silicon steel core is not suitable due to very heavy losses. The core loss and window length of AMCC 1000 are 91.83 mW/cm^3 at 0.2 T & 10 kHz and 40 mm respectively, similarly the core loss and window length of Ferrite core for power transformer U 126/91/20 are 70 mW/cm^3 at 0.2 T & 10 kHz and 70 mm respectively, therefore Ferrite core U126/91/20 and I126/28/20 has been selected for this application as per aforementioned criteria. The permeability of UU 126/182/20 is 2000. The core type construction has been implemented for making the HV & HF transformer. The special cage having 2 nos. of Acrylic sheets, 2 nos. of SS plates and 36 nos. of SS rods has constructed for supporting two pairs of UIU 126/344/240 in core type structure and is shown in Fig. 19.2(b).

Table 19.3: High Voltage Insulation properties of solid dielectric.

Insulating Material	Electrical Breakdown Strength	Dielectric Constant	Dissipation Factor	Temperature Class
Kapton	7.7 kV/mil	3.4	0.0018	C
Mylar	11 kV/mil	3.3	0.0025	C
Enamel	1 kV per turn	-	-	H *Solderable > 130 °C
Delrin 500P	19.7 kV/mm Arc resistance 220 No Tracking	3.7	0.005	<175 °C
FRP G11	14 kV/mm Arc resistance 130 -140	4-5	0.03-0.04	-

19.1.3 Ferrite Core Assembly Details

Assembled core cross-section area is 134.4 cm^2.
Window area is $70 \times 252 = 176.4$ cm^2.
Total height, width and length are 308 mm, 252 mm and 240 mm respectively.
Net core weight is 45.6 kg.

Table 19.4: Thermal class of Magnet Wire.

Class	**Temperature**
O	90
A	105
E	120 (IEC)
B	130
F	155
H	180
200(K)	200
220(M)	220
C	240+
250	250 (IEC)

The code of four letters mentioned in Table 19.4 for a transformer is described in Table 19.5.

Table 19.5: BS EN 60076-2 deals with temperature-rise.

1)	The first letter refers to the type of internal cooling medium contact with the windings	
	O	Mineral oil or synthetic insulating liquid with afire point $\leq$ 300 ℃
	K	Insulating liquid with fire point $>$ 300 ℃
	L	Insulating liquid with no measurable fire point
2)	The second letter refers to the circulation mechanism for the internal cooling medium from the options described below	
	N	Natural thermo siphon flow through cooling equipment and windings
	F	Forced circulation through cooling equipment, thermo siphon through windings
	D	Forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings.
3)	The third letter refers to the external cooling medium, thus	
	A	Air
	W	Water
4)	The fourth letter refers to the circulation mechanism for external cooling medium	
	N	Natural convection
	F	Forced circulation (fans, pumps).

The dimensions ($l \times w \times thk.$) of support acrylic and SS plate for assembly are 480 mm $\times$ 440 mm $\times$ 30 mm and 430 mm $\times$ 320 mm $\times$ 3 mm respectively.

Both items required quantity are 2 nos.

Table 19.6: Ratings of Secondary Winding.

Voltage	45 kV$_p$-0-45 kV$_p$
Frequency	10 kHz
Turns	720
Sections	16
Layer	9
Turns in each layer	5

19.1.4 Primary Bobbin

The length, width and height of the primary bobbin are 268 mm, 79 mm and 252 mm respectively. The MLT of the primary bobbin is 712 mm.

19.1.5 Secondary Bobbin

The length, width and height of the secondary bobbin are 336 mm, 130 mm and 222 mm respectively. The MLT of the secondary bobbin is 932 mm. The secondary bobbin has 16 sections. The leakage inductance is

$$L_l = 4\pi 10^{-4} \frac{N^2 l_w}{M^2 Y} \left(\frac{\sum x}{3} + \sum x_\Delta \right) \mu H \tag{19.1}$$

Where l_w : mean length of the winding.
Y : height of winding.
$\sum x$: winding thickness (P & S).
$\sum x_\Delta$: gap between the winding.

$$L = \frac{4 \times 3.14 \times 10^{-4} \times 16 \times 957.56}{252} \times \left(\frac{12.78 + 5}{3} + 29 \right) = 2.667 \ \mu H$$

The Capacitance of winding is defined as

$$C_a = \frac{\varepsilon \varepsilon_r A}{S_e} \quad F$$

$S_e = \Delta_i + 1.26 d_o - 1.15 d$
Where Δ_i = spacing between conductor
d_o= conductor dia
d = bare conductor dia
The SWG 17 wire has used in the secondary winding. Therefore the d, d$_o$ & Δ_i of SWG 17 wire are 1.422, 1.502 & 0.079 respectively.
$S_e = 0.079 + 1.26 \times 1.501 - 1.15 \times 1.422 = 0.33496 \ mm$

$$C_l = \frac{8.85 \times 10^{-12} \times 3.3 \times 983.12 \times 144 \times 10^{-6}}{0.33496 \times 10^{-3}} = 12.343 \ nF$$

The capacitance of each section has defined as below,

$$C = \frac{4C_l(p-1)}{3p^2q}$$

Where p = 9 (no. of layers); q = 16 (no. of sections).

$$C = \frac{4 \times 12.343 \times 8}{3 \times 81 \times 16} = 101.588\ pF$$

Therefore, the capacitance of the secondary winding is $C_a = \frac{C}{q} = 6.349\ pF$. The secondary winding to core capacitance (outer) in the oil is

$$C_o = \frac{8.85\ \times 10^{-12} \times 3.2 \times 240597.504 \times 10^{-6}}{30 \times 10^{-3}} = 227.124\ pF$$

Therefore, the core capacitance (outer) of the secondary winding due to sectioning effect is

$$C_b = \frac{C_o}{q} = 14.18\ pF.$$

Similarly, the secondary winding to core capacitance (inner) in the oil is

$$C_i = \frac{8.85\ \times 10^{-12} \times 3.2 \times 932 \times 252 \times 10^{-6}}{34 \times 10^{-3}} = 195.628\ pF$$

Therefore, the core capacitance (outer) of the secondary winding due to sectioning effect is

$$C_C = \frac{C_i}{q} = 12.25\ pF.$$

The total secondary capacitance is

$$C_S = \ C_a + \frac{C_b C_c}{C_b + C_C} = 6.349 + \frac{14.18 \times 12.25}{14.18 + 12.25} = 12.921\ pF\ \cong 13\ pF$$

19.1.6 Losses

The required cross-section area of primary copper wire is 100 mm^2. The resistivity of copper is 1.67×10^{-8} Ωm. The required length of the primary wire is 3.6 m. The resistance of the primary wire is

$$R_p = \frac{\rho\ l}{A} = \frac{1.67 \times 10^{-8} \times 3.6}{100 \times 10^{-4}} = 0.6012\ m\Omega$$

Similarly for the secondary winding

$$R_s = \frac{1.67 \times 10^{-8} \times 671.040}{1.583 \times 10^{-6}} = 7.0792\ \Omega$$

The skin depth for copper wire at 10 kHz frequency is

$$\Delta = \sqrt{\frac{\rho_c}{\pi \mu_o \mu_c f}} = \left(\frac{1.67 \times 10^{-8}}{3.14 \times 4 \times \pi \times 10^{-7} \times 1 \times 10000} \right)^{\frac{1}{2}} = 0.651\ mm$$

Now, 4Δ is 2.604 and the bare diameter, (d) of the copper conductor is 1.42 mm. If d is less than 4Δ, then the skin effect is negligible. The power loss in the primary winding is I^2R = $(339.4)^2 \times 0.6012 \times 10^{-3}$ = 69.25 W. The power loss in the secondary winding is I^2R = $(1.89)^2 \times 7.0792$ = 25.28 watt. The core loss is defined as product of core volume and power loss density, the core loss, P_c is 9.504×10^{-3} $m^3 \times 70 \times 10^3$ W/m^3 = 665.28 W. The total loss is core loss plus winding loss = 665.28 W + 69.25 W + 25.28 W = 759.81 W.

19.2 Electric Field Calculations and Insulations

The HV insulation is required between primary, secondary winding and core. The voltage per section of the HV winding is 6 kV and the thickness of Delrin between sections is 4 mm. The dielectric strength of Delrin is 19.7 kV/mm and the HV insulation of each section is 78.8 kV. The thickness of Delrin and HV insulation at both end of the bobbin are 5 mm and 98.5 kV respectively. Mylar having dielectric constant 3.25 at 1 kHz and dielectric strength 7.0 kV/mil has used for layer to layer to provide 625 V insulation. The voltage per turn of the HV winding is 125 V; hence no external insulation is required. The required gap for 45 kV in oil is 2.4 mm and the gap between the primary and secondary winding is 17 mm; which gives sufficient working safety factor over working voltages. There are two types of gap between HV winding and core, first gap is 15.5 mm between both end flanges of HV bobbin and core; therefore provided insulation in oil is 289.54 kV and similarly second gap is 18 mm between HV winding and core; hence the provided insulation in oil is 336.24 kV.

Table 19.7: Voltage distribution of HV winding sections from top to bottom.

S. No. (section)	**Voltage (kV)**	**Electric Field (kV/cm)**	**S. No. (section)**	**Voltage (kV)**	**Electric Field (kV/cm)**
1	45	93.46	9	-19.625	-11.68
2	39.375	81.77	10	-11.25	-23.36
3	33.75	70.09	11	-16.875	-319.05
4	28.125	58.4	12	-22.5	-46.73
5	22.5	46.73	13	-28.125	-58.4
6	16.875	319.05	14	-33.75	-70.09
7	11.25	23.36	15	-39.375	-81.77
8	19.625	11.68	16	-45	-93.46

Primary Delrin bobbin having length, width and height are 318 mm, 97 mm and 252 mm respectively. Skin depth at 10 kHz is 0.65 mm therefore 63 nos. of Litz wire having 200 strands with 1 mm^2 effective cross-section area has paralleled for making 4 turn primary of 712 mm MLT and 0.904 mΩ DC resistance. Secondary Delrin bobbin having length, width and height are 372 mm, 166 mm and 222 mm respectively with 16 sections has fabricated for 720 turn secondary. The SWG 17 has used in HV winding for making 5 turn in a layer and 9 layers in each section of 90 kV secondary bobbin. The MLT and DC resistance of HV winding are 983 mm and 7.1 Ω respectively.

The inductance of the 4-turn primary and leakage inductance of the transformer referred to primary are 380 μH and 2.667 μH respectively and coupling factor k between primary and secondary winding with ferrite core is 0.996. The total capacitance of HV secondary winding with 16 sections and the inductance of HV winding are 13 pF and 12.3 H respectively and maximum electric field of HV winding at 45 kV_P is 93.5 kV/cm. The Al value of the transformer is 23.75 μH. The equivalent circuit is shown in the Fig. 19.3(a) along with the photograph of the primary winding [Fig. 19.3(b)]. The designed natural resonance frequency and the efficiency at rated kVA of the transformer are 12.6 kHz and 99.4% respectively.

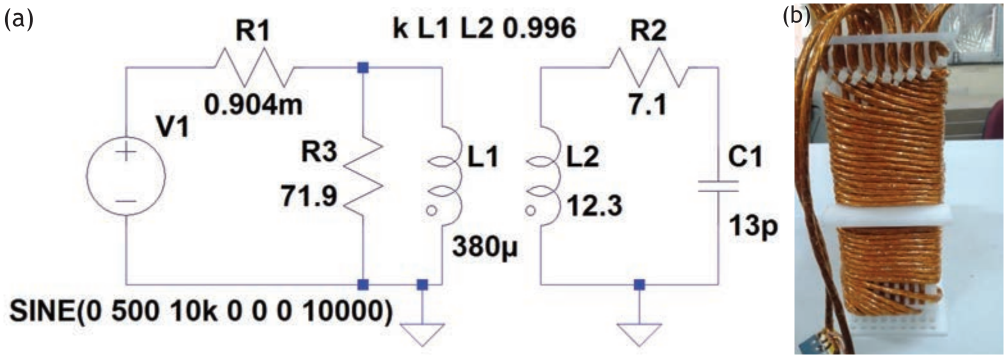

Figure 19.3: (a) The equivalent circuit of the transformer, and (b) photograph of Primary winding.

19.3 Assembly

19.3.1 Procedure for Making Primary Winding on the Primary Bobbin

1. Primary Delrin bobbin having length, width and height are 318 mm, 97 mm and 252 mm respectively.
2. Skin depth at 10 kHz is 0.65 mm.
3. 63 nos. of Litz wire having 200 strands with 1 mm^2 effective cross-section area have been paralleled for making 4-turn primary winding and MLT of primary winding is 712 mm.
4. The required length for making 4 turn primary winding using Litz wire is 3.6 m.
5. Make a set of 7 nos. of parallel Litz wire, 9 such sets complete the task of paralleling 63 nos. of Litz wire.
6. The total length of Litz wire required for making one set is 31.5 m. Insulate the whole length of Litz wire using Kapton tape with 50% over lap.
7. The total length of litz wire can be reduced to 4.5 m by making 7 folds. Now uniformly twist the folded litz wire and insulate the whole length of Litz wire using Kapton tape with 50% over lap. It completes the process of making first set of 7 nos. of parallel Litz wire.
8. Similarly, other 8 sets of 7 nos. of parallel Litz wire can be produced by using the above method.
9. Now wind the first set of Litz wire for making Four turn on the primary bobbin and inspect the winding as per photograph in Fig. 19.3(b).
10. Similarly, other 8 sets of Litz wire can be winded on the primary winding and inspect the winding as per photograph in Fig. 19.3(b).

19.3.2 Procedure for Making Secondary Winding on the Secondary Bobbin

1. Secondary Delrin bobbin having length, width and height are 372 mm, 166 mm and 222 mm respectively with 16 sections for 720 turn secondary winding.

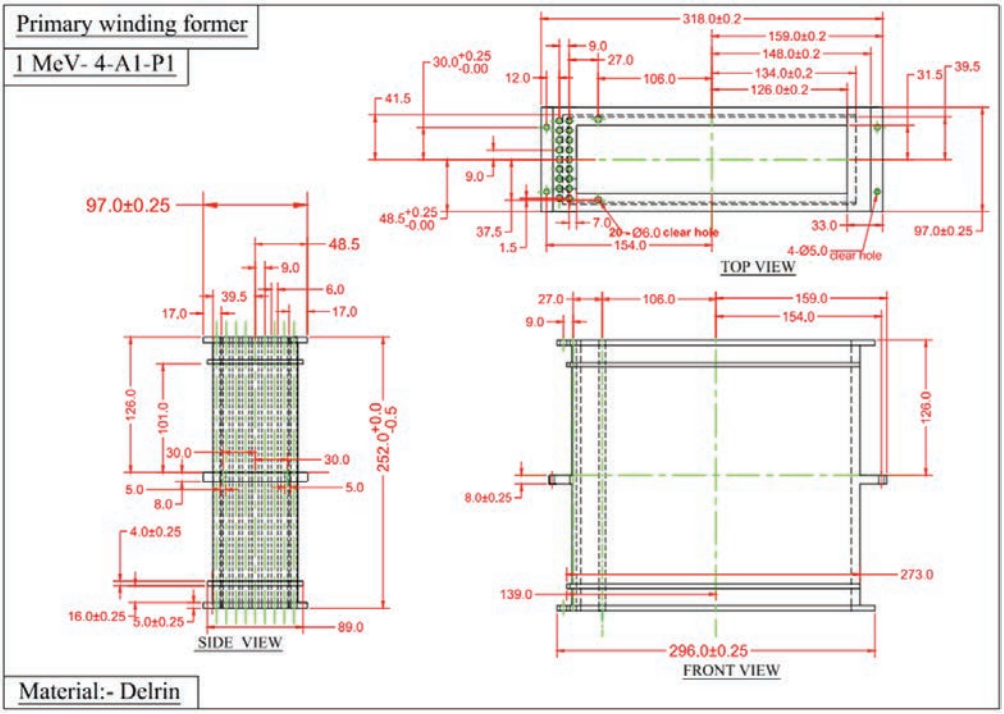

Figure 19.4: Drawing of transformer.

2. The SWG 17 has used in HV winding for making 5 turn in a layer and 9 layers in each section of 90 kV secondary bobbin.
3. The top and bottom of HV winding has maximum voltage, 45 kV and the middle of the HV winding is zero potential. Therefore, winding has divided in to two parts i.e. upper and lower winding.
4. Two layers of 9 mm width of Mylar sheet has to be winded into 16 sections of the secondary bobbin.
5. Both upper and bottom winding has 8 sections and should be commenced from middle of the secondary bobbin.
6. If the upper winding has started from middle in clock wise manner towards up ward direction then the bottom winding has started from middle in anti-clock wise manner towards down ward direction.
7. Single layer of 9 mm width of Mylar sheet has to be provided as layer to layer insulation after making 5 turns in a layer and similarly layer to layer Mylar insulation sheet should be provided after completing each layer.
8. Single SWG 17 wire should be used be for making 8 sections of upper winding and similarly single SWG 17 wire should be used be for making 8 sections of lower winding.
9. Additional 5 layers of 9 mm width of Mylar sheet should be provided in each 16 sections of secondary winding after completing both the upper and lower HV winding.
10. Additional Mylar sheet at middle of the winding should be provided for isolating both the zero-voltage end of the winding.

19.3.3 Assembly Procedure of Locking the Primary and Secondary Bobbin

1. First put the bottom of the completed primary winding on the table top so that the top view of primary bobbin can be checked easily.
2. Now put the completed secondary winding on the completed primary winding and check both the top of primary and secondary winding is matching as per drawing.
3. Lock the primary and secondary bobbin with help of 4 nos. M4 nut and bolts at specified place as per drawing.

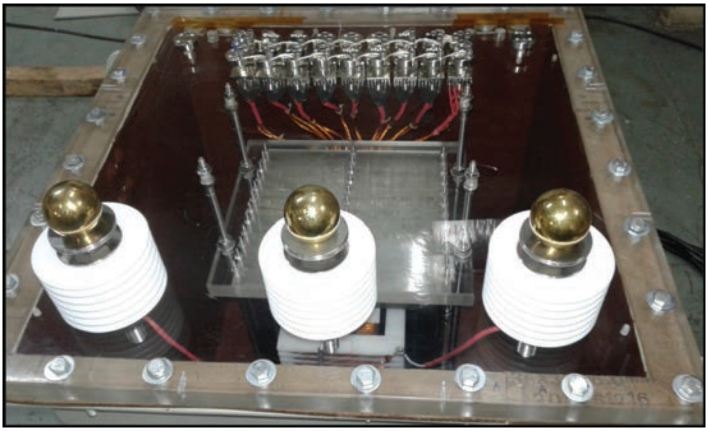

Figure 19.5: Top View of Transformer.

19.3.4 Assembly Procedure of Core with Primary and Secondary Winding

1. Two pairs of UIU 126/344/240 has bee constructed to achieve following parameters like cross-section area 134.3 cm^2, window area 176.4 cm^2 and weight 45.3 kg.
2. The special cage having 2 nos. of Acrylic sheets, 2 nos. of SS plates and 36 nos. of SS rods (as per drawings) has constructed for supporting two pairs of UIU 126/344/240 in core type structure.
3. 24 nos. of U 126/91/20 cores and 24 nos. of I 126/28/20 cores are selected for making a pair of UIU 126/344/240. Therefore total 48 nos. of U 126/91/20 cores and total 48 nos. of I 126/28/20 cores are required in the assembly.
4. 36 nos. of 430 mm long M4 SS rods has to be inserted in Bottom SS plates as per drawing. Acrylic sheet should be placed below the SS plate and locked with 36 nos. of M4 SS rods using 36 nos. of M4 nuts and washers. This first step of assembly should be check with help of drawing.
5. 48 nos. of M8 spring washer should be put at specified place in bottom ss plate.
6. 24 nos. of U 126/91/20 cores should be put and arranged as per drawing in the ss plate.
7. 48 nos. of I 126/28/20 cores should be put upon the 4 limbs of core assembly and check the assembly as per drawing.

8. Now put the assembled primary and secondary winding in the core type structure assembly and check the assembly as per drawing.
9. Put the 24 nos. of U 126/91/20 cores on the four limbs of the core type structure assembly and check the assembly as per drawing.
10. Put 48 nos. of M8 spring washers on the of U cores on the specified place as per drawing.
11. Put the top ss plate on the top of the complete assembly of core and windings.
12. Put the Acrylic sheet on the top of SS plate and lock the assembly with 36 nos. of M4 SS rods using M4 nuts and washers.
13. Check the entire assembly as per drawing.

19.3.5 Soldering of Primary Winding with Silver Plated Copper Lugs

1. Remove the 2″ of Kapton insulation and silk thread from both the ends of 63 nos. of parallel litz wire primary winding.
2. Both ends of 63 nos. of parallel litz wire primary winding should be properly tinned.
3. Now solder single bunch having 7 nos. of parallel litz wire of primary winding on the seven legs of a single Silver-plated Copper lug.
4. One end of primary winding has nine bunches therefore solder remaining eight bunches of primary winding with each eight Silver-plated Copper lugs (following step 3).
5. Similarly, the other end of nine bunches of primary winding should be solder with each nine Silver-plated Copper lugs (following step 3).
6. Total 18 nos. of Silver-plated Copper lugs having 7 legs has been used for soldering at both ends of 4 turn primary winding.
7. Check and inspect both the ends of primary winding with their Silver-plated Copper lugs.

19.3.6 Assembly of Transformer in the Tank with the Top Acrylic Cover

1. Insert 4 nos. of SS rod in the assembled transformer as per Fig 19.5 and lock the assembly with proper bolts.
2. Place the top acrylic cover on the 4 nos. of SS rod as per Fig. 19.5 and lock the assembly with proper bolt.
3. Check the assembly and leave the assembly for 2 hrs.
4. Connect the one end having 9 nos. of Silver-plated Copper lugs of 4 turn primary winding with the first set having 9 nos. of primary terminal with suitable nuts.
5. Similarly, connect the other end having 9 nos. of Silver-plated Copper lugs of 4 turn primary winding with the second set having 9 nos. of primary terminal with suitable nuts.
6. Connect the top end of HV winding having 16 sections with LHS HV terminal with suitable washer and nut and similarly, connect bottom end of HV winding having 16 sections with RHS HV terminal with suitable washer and nut.
7. Connect the centre of the HV winding having 16 sections with centre HV terminal with suitable washer and nut.

8. Now carefully lift the assembly and carefully put the assembly in the tank because the total weight of the assembly is 100 kg. Lock the tank with Top Acrylic cover with suitable nut and bolts.

19.4 Testing

Following tests needs to be conducted for determining the parameters like resistance of primary and secondary winding, leakage inductance, magnetizing inductance, coupling factor and step-up ratio.

a) Short circuit and open circuit test using LCR meter.

b) No load voltage test up to 15 kV without Transformer oil in the tank.

c) Load test up to 15 kV without transformer oil in the tank.

d) Full voltage test with transformer oil in the tank at No load.

The following measurements have been conducted for estimating the assembled HV & HF transformer in the tank with oil. The measured inductance of primary and secondary winding of the transformer after assembly in the tank at frequency 1 kHz are 413.2 μH and 12.3 H respectively and the achieved A_l value is 23.8 μH. The measured leakage inductance of the transformer at primary side and coupling factor k are 2.5 μH and 0.9969 respectively. The measured resistances of winding refer to primary and refer to secondary at 10 kHz are 7.76 mΩ and 303.4 Ω respectively. The Quality factor of the secondary HV winding with measured frequency is shown in Fig. 19.7. The breakdown voltage of spark gap A & B of the transformer at negative polarity dc voltage are 47.2 kV and 46.4 kV respectively and hence the geometrical factor of uniformity η of spark gap A & B are 0.88 and 0.87 respectively. The achieved step-up ratio of the transformer at no load, 40 kV, 10 kHz is 186 and temperature rise of oil during this 1.5 hr test run is 2.6 °C with copper coil cooling. The step-up ratio of the transformer at parallel load combination of capacitance 21 nF and wire wound resistance 348 kΩ at 12 kV, 10.8 kHz using full wave rectifier circuit is 197. The assembled 15 stage symmetrical Cockcroft–Walton HV multiplier has tested up to –900 kV DC potential at 33.5 kV transformer voltages, 10 kHz frequency using nitrogen gas at 6 kg/cm^2 pressure and the step-up ratio of the transformer is 204.

Table 19.8: Comparison of Design and Measured Parameters of Transformer.

Designed Parameter	**Designed Value**	**Measured Value**
Primary Resistance (mΩ)	0.904	7.76 @10 kHz refer to primary
Leakage Inductance (μH)	2.7	2.5
Core Resistance (Ω)	71.9	-
Magnetizing Inductance (μH)	380	413.2 @1 kHz
Secondary Resistance (Ω)	7.1	303.4 @10 kHz refer to secondary
Secondary Inductance (H)	19.3	19.3 @1 kHz
Coupling Factor (K)	0.996	0.997
Secondary Capacitance (pF)	13	93.2
A_l value (μH)	23.75	23.8
Efficiency (%)	99.4	-

19.4.1 Procedure for Determining the Stray Capacitance of HV Winding of the Transformer

During development of 125 kVA Transformer LCR meter test has been conducted for measuring O.C. & S.C. parameters but it cannot determine capacitance between HV and earth. This capacitance has been determined through connecting external capacitance between HV winding and earth. The procedure for determining the capacitance between HV winding and earth of the transformer is written below.

a) Connect the external capacitance greater than stray capacitance between HV winding and earth.

b) Finding the resonance frequency is the main exercise.

c) Step up ratio should be checked for determining the resonance frequency through applying the frequency from 50 Hz to 500 kHz.

d) Similarly connect second external capacitance greater than stray capacitance between HV winding and earth and check the second resonance frequency through applying the frequency from 50 Hz to 500 kHz.

We know that

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{19.2}$$

Now,

$$f_1 = \frac{1}{2\pi\sqrt{L\left(C_x + C_1\right)}} \tag{19.3}$$

$$f_2 = \frac{1}{2\pi\sqrt{L\left(C_x + C_2\right)}} \tag{19.4}$$

$$\text{therefore, } C_x = \frac{{f_2}^2 C_2 - {f_1}^2 C_1}{{f_1}^2 - {f_2}^2} \tag{19.5}$$

The stray capacitance of HV winding obtained through above procedure is 93.6 pF. This capacitance has explained, why step-up ratio is coming higher than the designed value at no load and also determine the higher cut off frequency of 360 kHz.

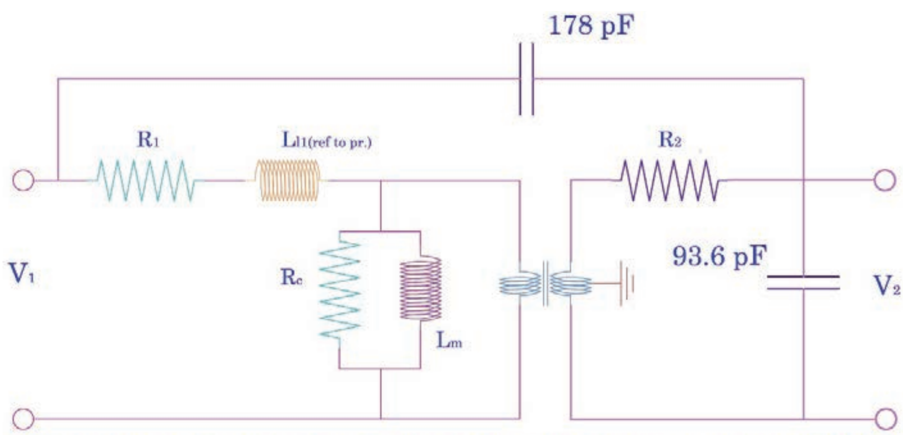

Figure 19.6: The HV & HF transformer equivalent circuit at frequency > 360 kHz.

19.4.2 Procedure for Determining the Stray Capacitance Between Primary and Secondary Winding of the Transformer

The Stray Capacitance between primary and secondary winding is most peculiar problem because energy transfer between primary and secondary winding is via magnetic core, therefore stray capacitance is actually shorting problem of the primary and secondary winding. The Step-up or Step-down logic of the transformer is only valid in lower cut off to higher cut off frequency region, therefore below the cut off frequency region, the primary winding of the transformer will act as load and heat the transformer. This leads to the burning of the transformer. Similarly, above the higher cut off frequency region, the transformer winding faces the shorting problem. Hence the problem of finding the stray capacitance between primary and secondary winding becomes a most interesting problem. There are two ways to solve this problem.

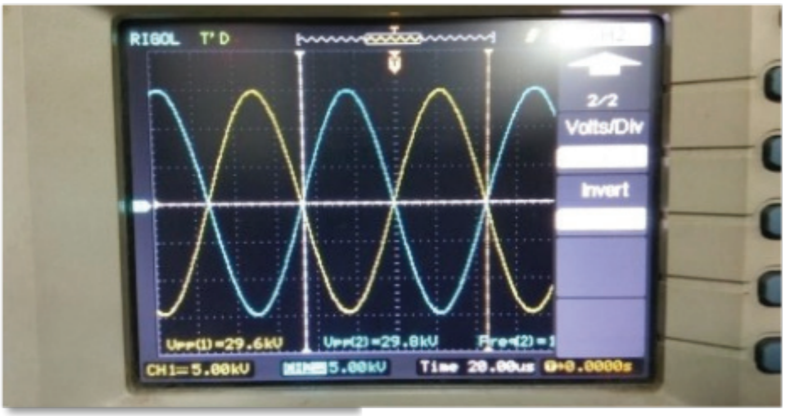

Figure 19.7: The transformer at No Load, 30 kV.

a) Calculate the geometric capacitance between the primary and secondary winding. There are no solutions available in the literature for this problem. This way is difficult for finding good and accurate solutions.
b) Measure the capacitance between primary and secondary winding from 20 Hz to 1 MHz range. This is a quick way to get some peculiar results and 178 pF capacitance in oil at 500 kHz has been measured between primary and secondary winding. This result is incomplete because there is no capacitance calculation and it is only measurements.

Now the logic of transformer becomes

i) resistive, $f < 20$ Hz;
ii) Step-up = 180 along with 93.6 pF between HV winding and earth, 20 Hz $< f <$ 360 kHz;
iii) primary to secondary capcitance = 178 pF along with 93.6 pF between HV winding and earth, $f >$ 360 kHz;

This spectrum of the transformer explains the complete circuit response.

Suggestions for Further Reading

a) [97–103]