CHAPTER III

EXPERIMENTS AND CHARACTERISTICS

3-1 Introduction

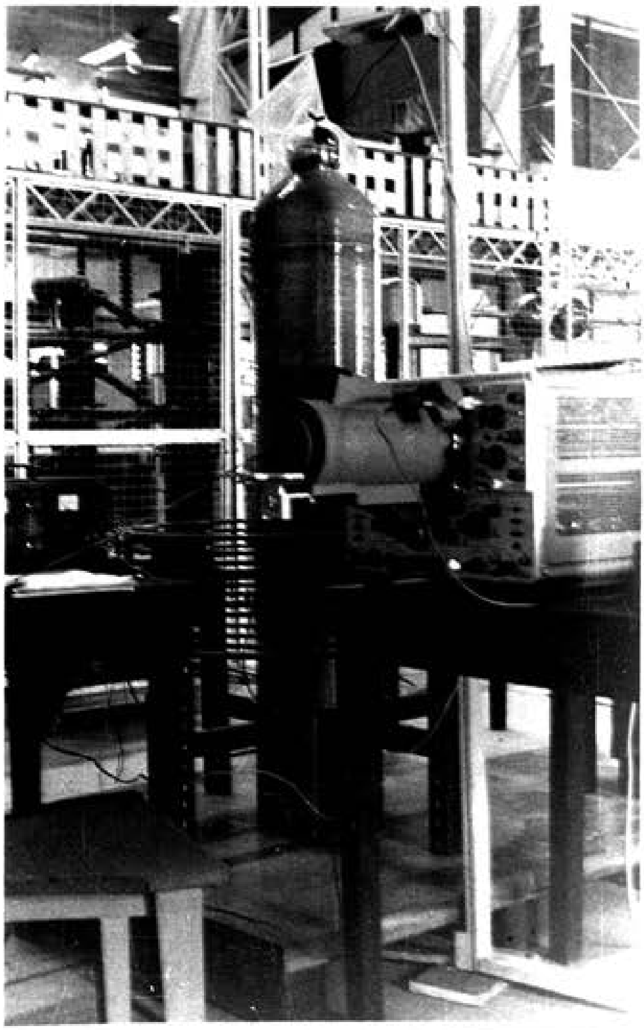

Fig.3-1 Completed set of Tesla Transformer.

This chapter is dealt with the experiments on High Voltage and Low Voltage coils or both of the completed Tesla

Transformer shown in Fig.3-1 to obtain its characteristics. The experiments go step by step from the lower value of voltage to the higher value (i.e. from 1.5 v, 10 v and 23 Kv.D.C. of the applied voltage). If the gap-distance is longer than the radius of the sphere-gaps, the voltage output of the Tesla Transformer measured by this sphere-gaps (25 cm. diameter) is not accurately enough. Then, the characteristics at the 23 Kv.D.C. source is assumed to be its characteristics when the output is about 1,000 Kv.

3-2 Experiment and Characteristics of the H.V. coil at 1.5 V., D.C. supply

With reference to Fig.2-4 and Fig.2-5, the Oscillating frequency is calculated about 128 Kcs. This value is lower and about 100 Kcs. when it is actual operation. The stray capacitance of the High Voltage coil based on 100 Kcs. is :

$$Cs_2 = \frac{1}{4\pi^2 f^2 L_2}$$

where L_2 = 28.6 mh.

$$\therefore \; Cs_2 = \frac{1}{4\pi^2 (100\times10^3)^2 (28.6\times10^{-3})}$$

$$= 88.5 \text{ pF.}$$

The High frequency resistance of the High Voltage coil is calculated from the Oscillating frequency in Fig.2-5.

Then, from section 1-4e.

$$R_2 = \frac{2L}{T} \ln \frac{i_t}{i_{t+T}}$$

$$= \frac{2x28.6x10^{-3}}{7.8x10^{-6}} \ln \frac{1.61}{1.57}$$

$$= \frac{2x28.6x10^{-3}}{7.8x10^{-6}} x0.027$$

$$= 198.1 \text{ ohms.}$$

By measurement with the high frequency ohm-meter

$$R_2 = 210 \text{ ohms.}$$

Therefore, the High frequency resistance of H.V. coil is

$$R_2 = \frac{210+198.1}{2} = \underline{204.05 \text{ ohms}}.$$

3-3 Experiment and Characteristics of the Tesla Transformer at 10 V., D.C. supply

The circuit is arranged as shown in Fig.3-2.

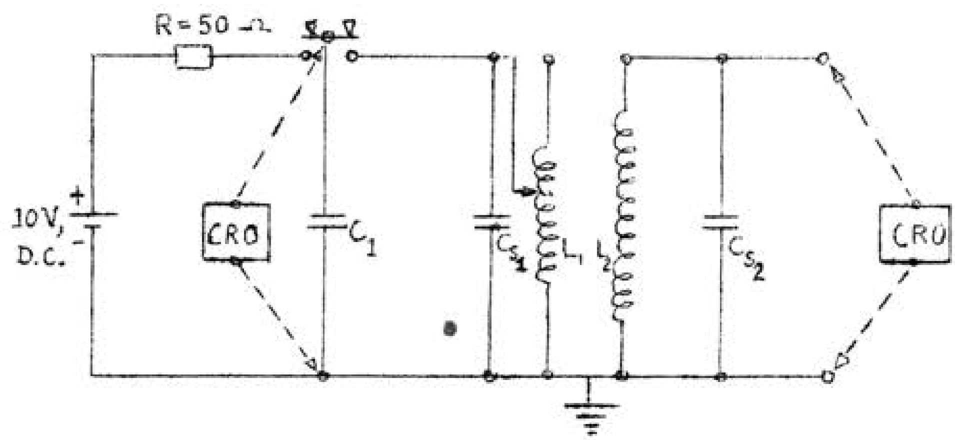

Fig.3-2 Equivalent circuit of Tesla Transformer at 10 V, D.C. supply.

R is the current limit-ing resistance (radio work types). The Voltage output and Oscillating frequency characteristics are obtained by displaying on the Double Beam Oscilloscope connected as shown. Their characteristics are recorded by taking the pictures.

3-3a <u>The Oscillating frequencies characteristics of the two coils</u>. From the design data in section 2-3b, the carbon capacitances (8,000, 15,600 and 62,500 pF) is used to observe roughly the oscillation that appears on CRO. The number of turns and the positions of Low Voltage coil are varied. There is no oscillation appearing on CRO at the other values of the capacitance except at 62,500 pF capacitance.

So, concentrated at 62,500 pF capacitance, the position of Low Voltage coil is fixed at any position. Then, the number of turns is fixed and observing the oscillation on CRO. At 4 turns, the Oscillating frequencies on both coils is the same and recorded as shown in Fig.3-3. The Double Beam Oscilloscope is setting as follows.

<u>L.V. Coil (Upper beam in Fig.3-3)</u>

Volts/Div. at 0.5

Time/Div. at 10 μsec

<u>H.V. Coil (Lower beam in Fig.3-3)</u>

Volts/Div. at 0.05

Time/Div. at 10 μsec

The probe is used on High Voltage side and attenuated

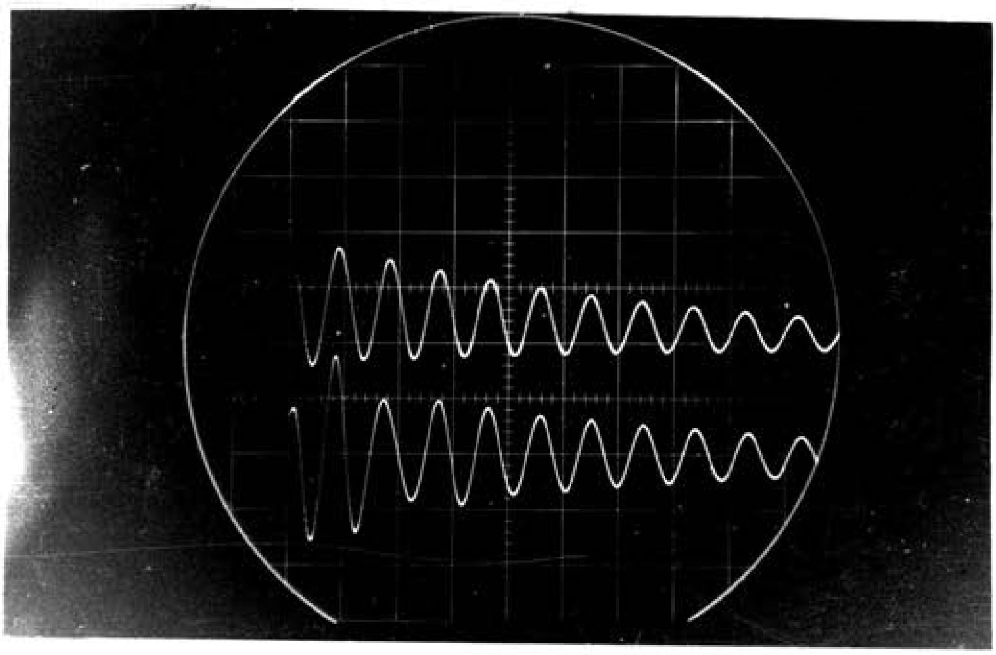

Fig.3-3 Oscillating frequencies characteristic of the Tesla Transformer at Position 11, 4 turns and 10 V,D.C. supply.

1,000 times. Referred to Fig.3-3, the L.V. and H.V. coils oscilates the same frequency with 0.95 division for one cycle.

Then, the period for one cycle, $T = 0.95 \times 10 \times 10^{-6}$ sec

$$\therefore f = \frac{1}{T} = \frac{1}{0.95 \times 10 \times 10^{-6}} = 105 \text{ Kcs.}$$

3-3b Maximum Voltage Output Characteristic of the Tesla Transformer. To obtain the maximum Voltage Output characteristic, the number of turns is fixed at 4 turns and the positions of L.V. coil is varied. The peak value of oscillation of H.V. coil observed on CRO is tabulated in the table below :

Positions of L.V.coil	Peak values of oscillation of H.V. coil. (Divisions)	Maximum Voltage Output of H.V. coil. (Volts)
1	0.7	0.7x0.05x1,000 = 35
2	0.8	0.8x0.05x1,000 = 40
3	0.9	0.9x0.05x1,000 = 45
4	1.1	1.1x0.05x1,000 = 55
5	1.2	1.2x0.05x1,000 = 60
6	1.3	1.3x0.05x1,000 = 65
7	1.4	1.4x0.05x1,000 = 70
8	1.5	1.5x0.05x1,000 = 75
9	1.6	1.6x0.05x1,000 = 80
10	1.7	1.7x0.05x1,000 = 85
11	1.8	1.8x0.05x1,000 = 90

The maximum Voltage Output of H.V. coil is calculated from the voltage at the tip of the probe, the volts per division of the CRO setting of the H.V. coil, and the peak value of the oscillation of H.V. coil. Then, the maximum Voltage Output = Division (peak) x Volts/Div. x Probe attenuated; e.g. at position 1 the maximum Voltage Output = 0.7 x 0.05 x 1,000 = 35 volts. The other values are calculated in the same way as shown in the table.

It is noticed that the maximum Voltage Output occurs at position 11 of the L.V. coil and about 90 volts. Its

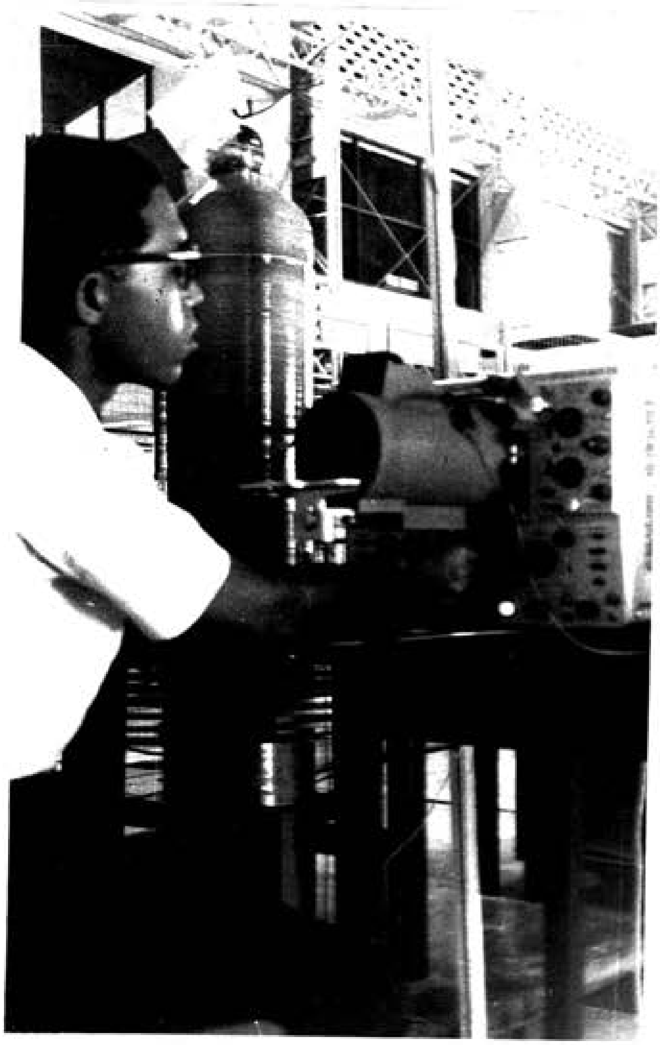

Fig.3-4 Measurement of Oscillating frequencies on both coils and maximum Voltage Output at 10V, D.C. supply.

value is about 9 times campared with the applied voltage (10 volts) and the same Oscillating frequencies occurring on the H.V. and L.V. coil is at 4 turns.

3-4 Experiment and Characteristics of the Tesla Transformer at 23 Kv, D.C. supply

The characteristics are obtained by arranging the circuit as shown in Fig.3-5.

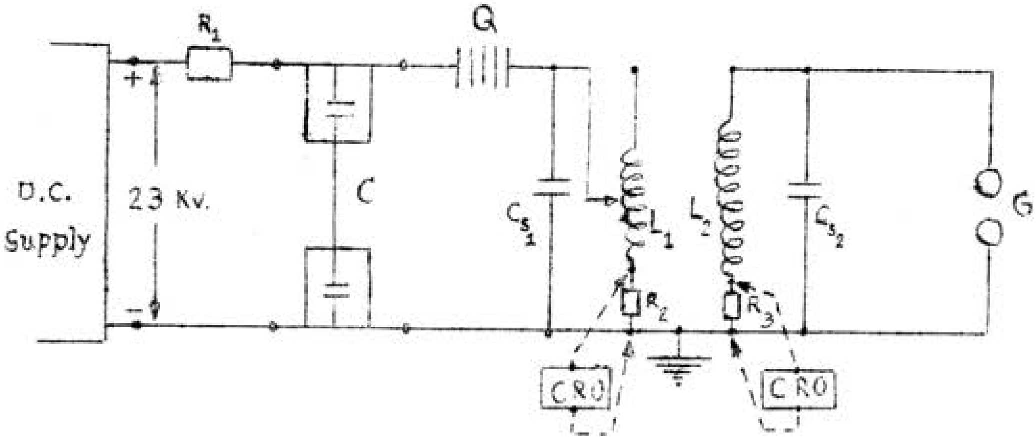

Fig.3-5 Equivalent circuit of the Tesla Transformer at 23 Kv, D.C. supply.

Where, C = 2 oil condensers of 0.125 μF connected in series

= 62,500 pF.

Q = Quenched-air gap for controlling the discharging of condenser, C.

L_2 = Inductance of H.V. coil

= 28.6 mh.

Cs_2 = Stray capacitance of H.V. coil

= 88.5 pF.

L_1 = Inductance of L.V. coil

= 4.05×10^{-2} mh. at 4 turns

R_1 = Two water resistance (as a current limit-ing resistance) connected in series.

= 1.4 Mega-ohms.

R_2 = Shunt resistance 60 mV, 600 A for observing the current wave form of the L.V. coil on CRO

= 0.1 milli-ohm.

R_3 = Carbon resistance for observing the current wave form of the H.V. coil on CRO

= 0.1 ohm.

G = 25 cm. diameter sphere-gaps for Voltage Output measurement.

By the experiment in the last section, the same Oscillating frequencies on H.V. and L.V. coils occur at 4 turns of L.V. coil and the maximum Voltage Output of the H.V. coil obtained at position 11 of the L.V. coil; so the characteristics of the Tesla Transformer are interested at these values.

3-4a Voltage Output vs. Positions of the L.V. coil Characteristic at 4 turns, 23 Kv., D.C. supply. To obtain this Characteristic, the circuit is arranged as shown in Fig. 3-6. Q is the quenched-air gap setting at 15 sec. discharging interval of the capacitance, C. L_1 is fixed at 4 turns. By varying the positions of L.V. coil and observing the spacing distances at 50 percent breakdown between the two sphere-gaps, G; the results are obtained.

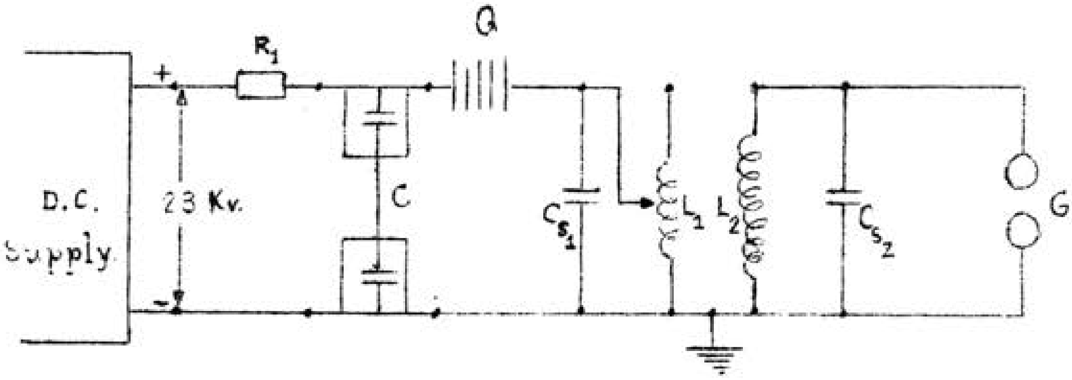

Fig.3-6 Equivalent circuit of the Tesla Transformer for obtaining the Characteristic Curves with 23 Kv., D.C. supply.

Experimental Data

Positions of L.V. coil at 4 turns	Spacing distance at 50% breakdown (cm.)	Pressure and Temperature during the experiment
11	7.9	p = 765 mm. Hg.
9	7.4	t = 27.4°C
7	6.8	
5	6.1	
3	5.2	
1	4.3	

From the Experimental Data, the breakdown voltage, Us at 50 cps. in Kv. is found from Appendix A. The Voltage Output of the H.V. coil at 105 Kcs. is calculated from section 1-9b and multiplied this results by 0.9 (the frequency is 105 Kcs. higher than the power frequency or 50 cps.).

The relative air density, d in this case is

$$d = 0.386 \left(\frac{p}{273+t}\right)$$

$$= 0.386 \left(\frac{765}{273+27.4}\right)$$

$$= 0.96$$

Then, from section 1-9b, the Voltage Output is $d \times U_s \times 0.9$ and U_s is found from Appendix A.

Example of calculation the Voltage Output, from the Experimental Data at Position 11, the spacing distance is 7.9 the breakdown voltage at 50 cps. is 203 Kv. (from Appendix A).

Hence, the Voltage Output of H.V. coil at 105 Kcs.

$$= 0.96 \times 203 \times 0.9$$

$$= 179 \text{ Kv.}$$

The other values of the Voltage Output is calculated in the same way and tabulated in the Calculated Data.

The Characteristic curve is plotted the Positions of L.V. coil at 4 turns against the Voltage Output of H.V. coil at 105 Kcs. as shown in Fig. 3-7. It is noticed that the Voltage Output increases with the Positions of L.V. coil. The maximum Voltage Output occurs at the highest Position (Position 11) of the L.V. coil. Its value is about 179 Kv. and about 9 times of the supplied voltage (23 Kv.).

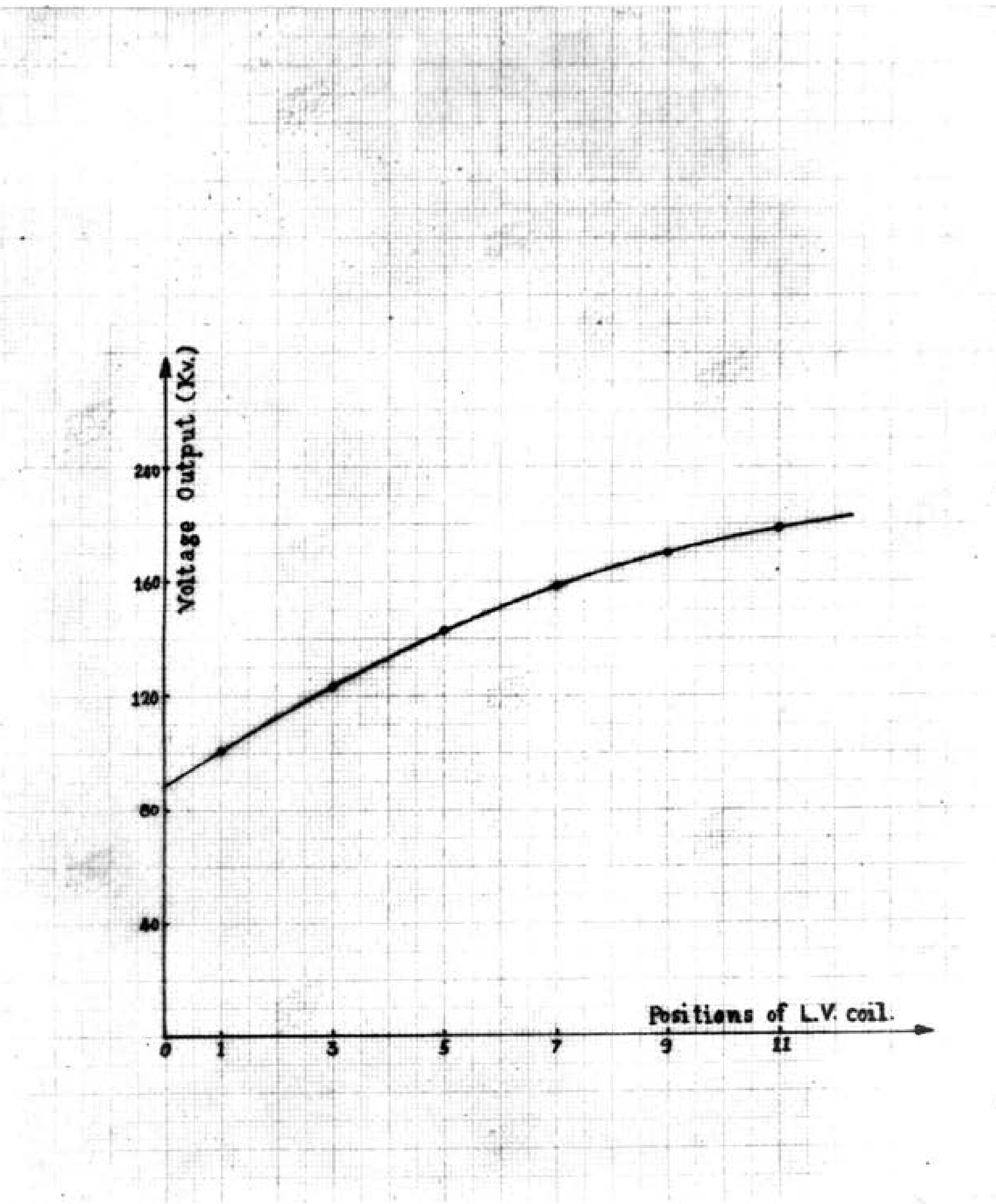

Fig.3-7 Characteristic curve of Voltage Output vs. Positions of L.V. coil of the Tesla Transformer at 4 turns and 23 Kv., D.C. supply.

Calculated Data

Positions of L.V. coil at 4 turns	Spacing distance (cm.)	Breakdown Voltage, U_s at 50 cps. (Appendix A, in Kv)	Voltage Output of H.V. coil at 105 Kcs. (Kv.)
11	7.9	203	179
9	7.4	193	171
7	6.8	180	159
5	6.1	162	143.8
3	5.2	140	124
1	4.3	114	101

3-4b Voltage Output vs. Number of turns of L.V. coil Characteristic at Position 11, 23 Kv., D.C. supply. The Characteristic is obtained by referring to Fig.3-6, in which L_1 is fixed at Position 11 and the number of turns is varied from 1 turn to 10 turns. The spacing distances between the two sphere-gaps at 50 percent breakdown are observed. The quenched-air gap, Q is setting at 15 sec. discharging interval. The pressure and temperature during the experiment are also observed. The results are shown in the Experimental Data. From this Data, the breakdown voltage is found from Appendix A and the Voltage Output of H.V. coil at different positions is calculated from section 1-9b. in same way as the last section. The results are shown in the Calculated Data.

Experimental Data		Calculated Data	
Number of turns	Spacing distance (cm.)	Breakdown Voltage, U_s at 50 cps.(Kv) (From Appendix A)	Voltage Output of H.V.coil at 105 Kcs. (Kv.)
1	1.7	40	35.3
2	4.2	112	98.7
3	7.3	191	168
4	7.9	203	178
5	6.6	173	153
6	5.9	158	139
7	4.8	132	116
8	4.5	122	107
9	4.0	110	97
10	3.3	92	81

The pressure and temperature during the experiment are :

$$p = 765 \text{ mm. Hg.}$$

$$t = 29.5^{\circ}C$$

The relative air density in this case is

$$d = 0.386 \times \frac{765}{273+29.5}$$

$$= 0.955$$

The Number of turns and the Voltage Output is plotted as a Characteristic curve shown in Fig.3-8 at Position 11. It is noticed that the Voltage Output increases as

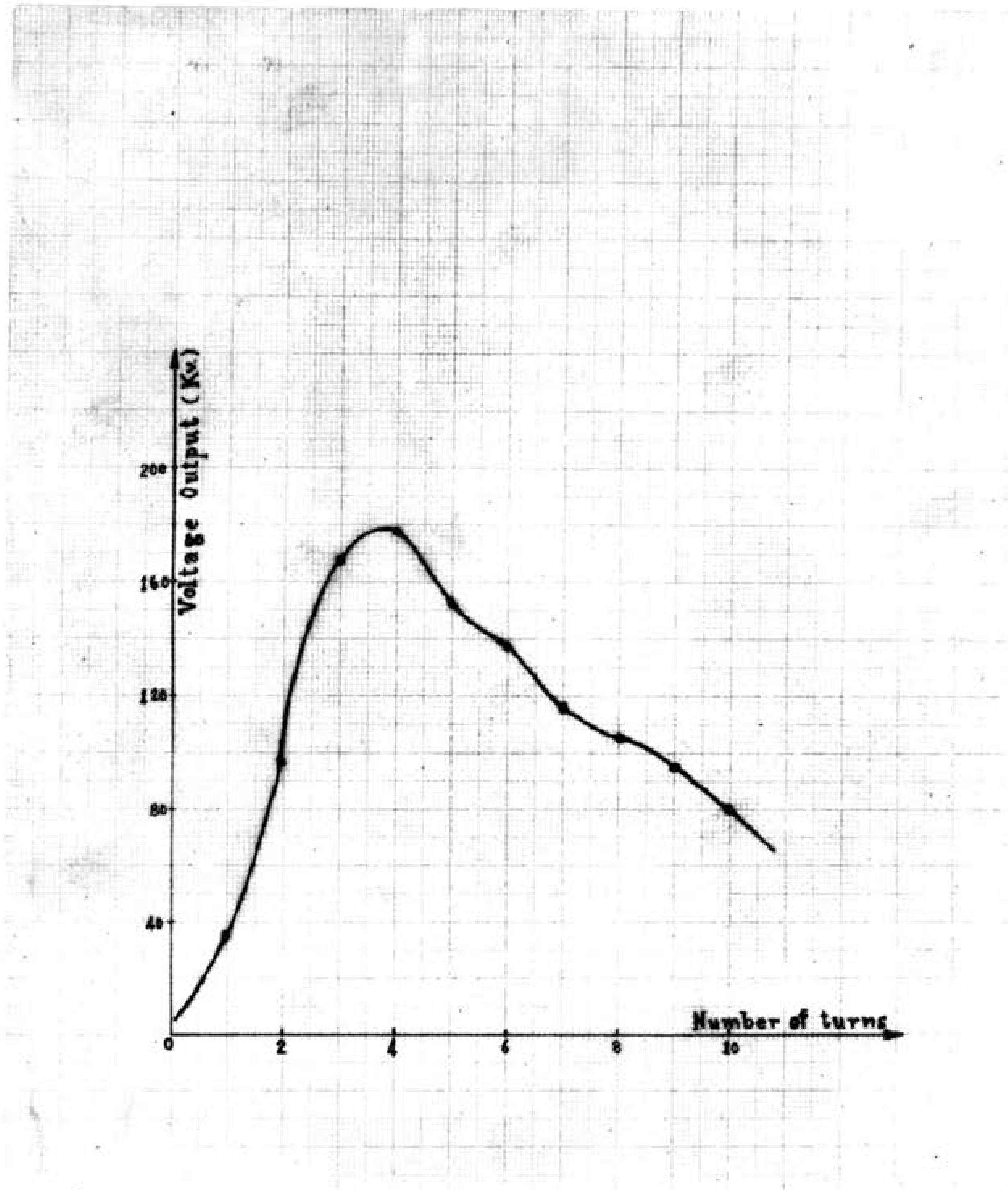

Fig.3-8 Characteristic curve of Voltage Output vs. Number of turns of Tesla Transformer at Position 11 and 23 Kv., D.C. supply.

the Number of turns; and maximum at 4 turns about 178 Kv. Then it decreases as the Number of turns increases.

3-4c <u>Current wave-form Characteristics of the Tesla Transformer at 4 turns, Position 11 and Position 1</u>. The wave-form Characteristics of the Tesla Transformer are obtained by arranging the circuit as shown in Fig.3-9.

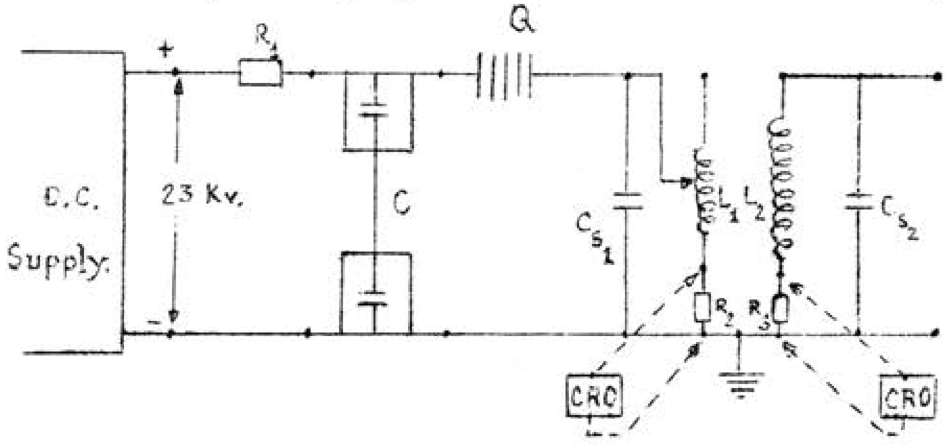

Fig.3-9 Equivalent circuit of the Tesla Transformer for obtaining the wave-form Characteristics at 4 turns, 23 Kv.,D.C. supply.

The Double-beam Oscilloscope is used for obtaining the current wave-form Characteristics as shown in Fig.3-10 and Fig.3-11 at 4 turns, Position 11 and Position 1 of the L.V. coil respectively. In the Figures, the upper wave-form is the L.V. wave-form and the lower one is the H.V. wave-form.

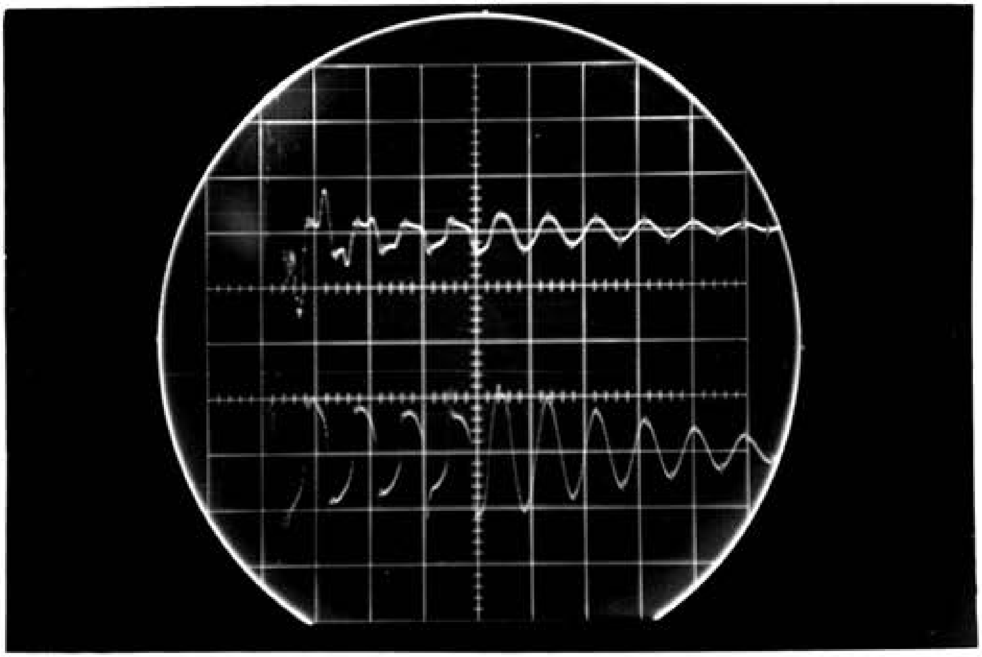

Fig.3-10 Current wave-form Characteristic of the Tesla Transformer at 4 turns, Position 11.

3-5 Mutual inductance and Coefficient of coupling of the Tesla Transformer.

The Mutual inductance can be either calculated or measured. The Coefficient of coupling is calculated from the relation $K = \frac{M}{\sqrt{L_1 L_1}}$

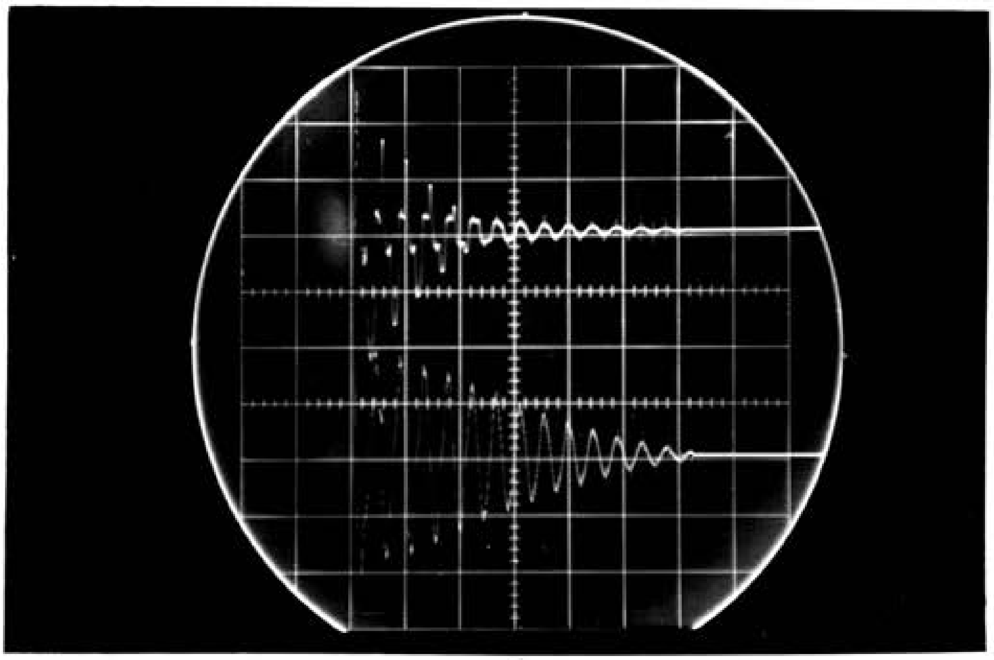

Fig.3-11 Current wave-form Characteristic of the Tesla Transformer at 4 turns, Position 1.

3-5a <u>By Calculation</u>. The Mutual inductance is calculated from Appendix B(3) and the parameters are as shown in Fig. 3-12 and Fig.3-13.

<u>At 4 turns, Position 11</u>

From Appendix B(3),

$a = 14.25$ cm. (5.62 inch)

$A = 40$ cm. (15.7 inch)

$k_1 = 2\ell = 114.5$ cm. (45.1 inch)

$2x = 10$ cm. (3.94 inch)

$n_1 = 4$ turns

$n_2 = 670$ turns

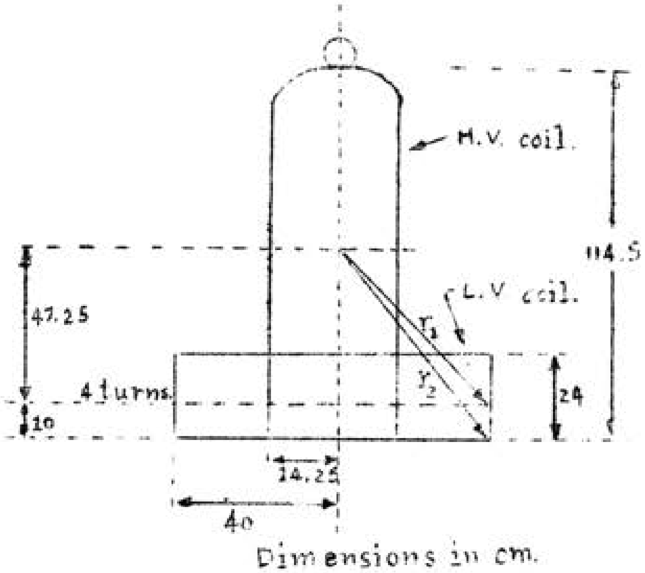

Fig.3-12 Dimensions of the Tesla Transformer for calculating Mutual inductance at 4 turns, Position 11.

$x_1 = 47.25$ cm. (18.6 inch)

$x_2 = 57.25$ cm. (22.6 inch)

$r_1 = \sqrt{(47.25)^2+(40)^2} = 60.1$ cm. (24.6 inch)

$r_2 = \sqrt{(57.25)^2+(40)^2} = 68.3$ cm. (27.3 inch)

$\therefore M_{11} = 0.001326$ h.

Hence, $K_{11} = \dfrac{0.001326}{\sqrt{4.05\text{x}10^{-5}\text{x}28.6\text{x}10^{-3}}}$

$= 1.01$

<u>At 4 turns, Position 1</u>.

From Appendix B(3),

$a = 14.25$ cm. (5.62 inch)

$A = 40$ cm. (15.7 inch)

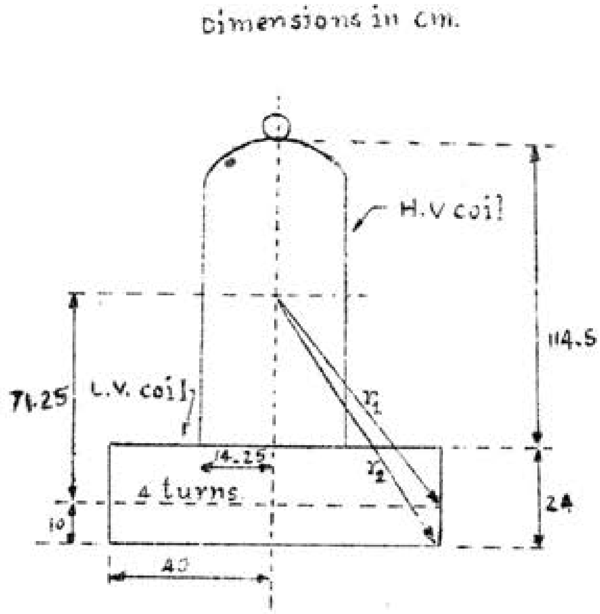

Fig.3-13 Dimensions of the Tesla Transformer for calculating Mutual inductance at 4 turns, Position 1.

$$k_1 = 2\ell = 114.5 \text{ cm. } (45.1 \text{ inch})$$

$$2x = 10 \text{ cm. } (3.94 \text{ inch})$$

$$n_1 = 4 \text{ turns}$$

$$n_2 = 670 \text{ turns}$$

$$x_1 = 71.25 \text{ cm. } (28.1 \text{ inch})$$

$$x_2 = 81.25 \text{ cm. } (32.1 \text{ inch})$$

$$r_1 = \sqrt{(71.25)^2 + (40)^2} = 80.7 \text{ cm. } (32.3 \text{ inch})$$

$$r_2 = \sqrt{(81.25)^2 + (40)^2} = 88.2 \text{ cm. } (35.5 \text{ inch})$$

$$\therefore \quad M_1 = 0.000325$$

Hence, $K_1 = \dfrac{0.000325}{\sqrt{4.05\times10^{-5}\times28.6\times10^{-3}}} = 0.34$

3-5b By Measurement. The circuit is arranged as shown in Fig.3-14(a) and (b). L and L' are measured and M is found from section 1-2.

Fig.3-14 Equivalent circuit of H.V. and L.V. coil for measurement of Mutual inductance.

At 4 turns, Position 11.

From section 1-2, $M = \frac{L - L'}{4}$

where L = 28 mh. (by measuring)

L' = 25 mh. (by measuring)

$\therefore M_{11} = \frac{3}{4} = 0.75$ mh.

Hence, $K_{11} = \frac{0.75 \times 10^{-3}}{10.67 \times 10^{-4}}$

$= 0.703$

At 4 turns, Position 1.

By measuring, L = 32.5 mh.

L' = 32.0 mh.

$\therefore M_1 = \frac{0.5}{4} = 0.125$

Hence, $K_1 = \frac{0.125 \times 10^{-3}}{10.67 \times 10^{-4}}$

$= 0.117$

It is noticed that the calculated values of the coefficient of coupling are higher than the measured value; it is because of the formula used is a roughly approximation.

So, on the average $K_{11} = \frac{1.01+0.703}{2} = 0.856$ and

$K_1 = \frac{0.34 + 0.117}{2} = 0.228$

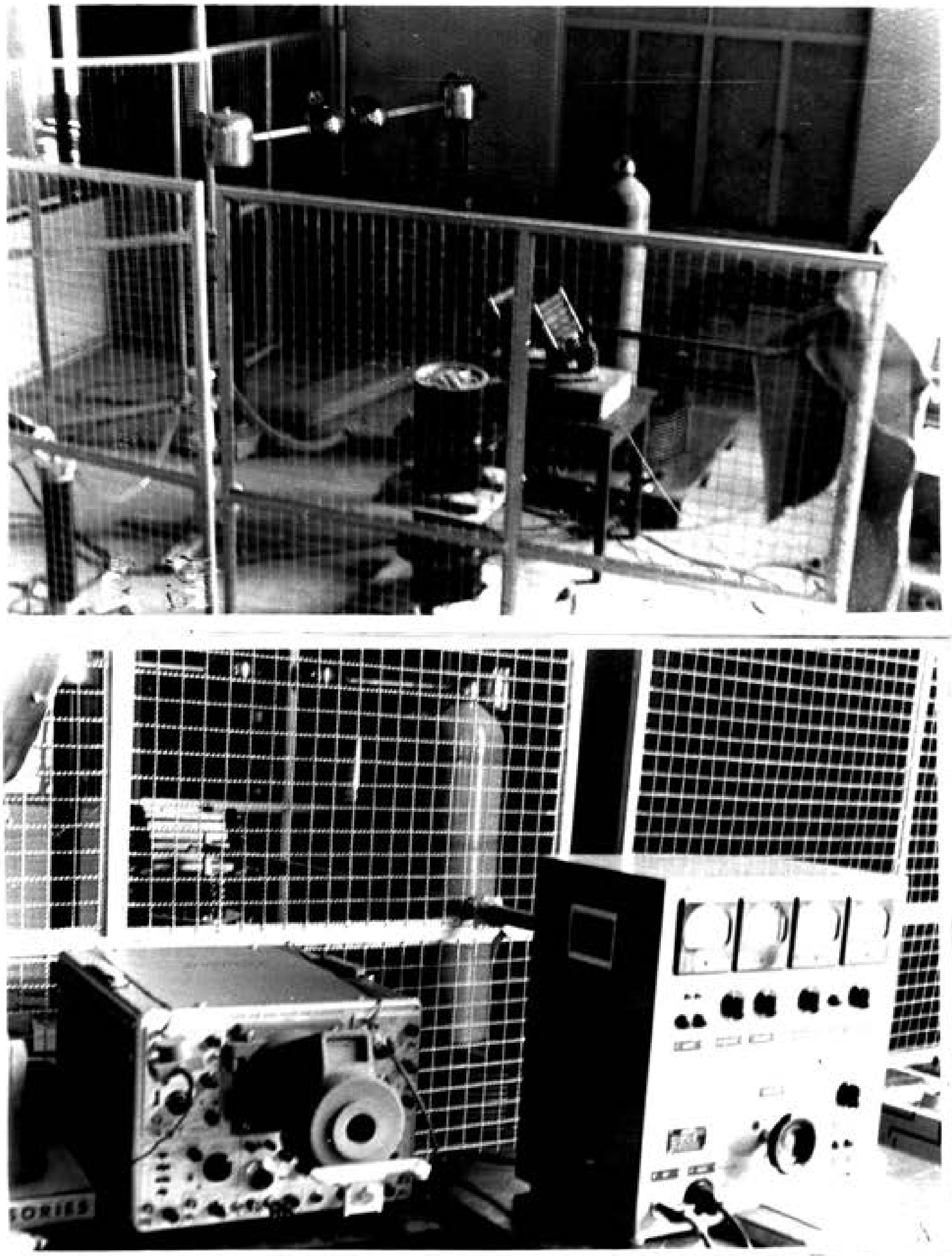

Fig.3-15 Arrangement for measuring Voltage Output and Wave-forms Characteristics of the Tesla Transformer.

3-6 Summaries and Conclusions

Coming up to this point, the summaries and conclusions can be stated as :

1) The Oscillating frequency is lower when the capacitance and inductance is increased, so the leads connection between the apparatus should be as shortest as possible.
2) The smallest value of the capacitances that the Tesla Transformer should start to work is 62,500 pF. This is because of the capacitance between conductors of L.V. coil is high.
3) The design data is shown in section 2-3.
4) The characteristic curve of Voltage output vs. different Position of L.V. coil at 4 turns is shown in Fig. 3-7.
5) The characteristic curve of Voltage output vs. Number of turns at position 11 is shown in Fig.3-8.
6) The Oscillating frequency is the same on both coils at 4 turns and the maximum voltage output is at position 11. This is because of tight coupling at position 11.
7) Noticing from the last two experiments the voltage output is about 9 times of the supplied source. That is, the maximum voltage output, 178 Kv. at 23 Kv. supply causes the gap distance to be 7.9 cm. If the Voltage output were 1,000 Kv. about

5 times more, the gap distance should be 40 cm.

Hence, 25 cm. diameter sphere-gaps is not enough accuracy (spacing distance not more than the radius of the sphere-gaps), so, it is recommended to use 50 cm. diameter sphere-gaps to test this voltage output. For this purpose, it may be considered that at 23 Kv. source should be the operating characteristics.

8) The wave-forms of the Tesla Transformer obtained by this experiment is the Current wave-forms but they are not different capared with the Voltage wave-forms. The Current wave-forms at the highest (Position 11) and lowest (Position 1) positions with 4 turns are shown in Fig.3-10 and Fig.3-11 respectively.

The lower beam is of the H.V. side. There are differences between these two positions because of the effects of mutual inductance or coefficient of coupling which are very important. At position 11, the coupling is about 0.856, usually high coupling and the wave form is corresponding to the ideal Tesla Transformer in Fig.1-3. At position 1, the coupling is about 0.228 rather low coupling and the wave-form corresponds to the ideal case discussed by Goodlet shown on Fig.1-4.

While, the upper beam is of the L.V. side and the wave-form is not interrupted. So, there is no enery staying in the H.V. side. This effect should be carefully studied the quenched-gap being used and left to be studied by the person interested in this field to carried out.

9) There is a harmonic distortion, and corona on the L.V. coil.

10) The parameters of the Tesla Transformer are

<u>L.V. coil</u> :

$L_1 = 4.05 \times 10^{-2}$ mh. at 4 turns

$C_1 = 62,500$ pF.

<u>H.V. coil</u> :

$L_2 = 28.6$ mh.

$Cs_2 = 88.5$ pF.

R (high frequency) = 204.05 ohms.

<u>Coefficient of coupling</u>:

At position 11, 4 turns,

$K_{11} = 0.856$

At position 1, 4 turns,

$K_1 = 0.228$

Current limiting resistance based on 250 Kva. transformer is 50 Kilo-ohms and Power dissipated 50 Kilo-watts.

The other parameters of the Tesla Transformer can be found in the Sign Data, section 2-3b.