PRODUCTION OF STANDARD WAVES WITH A 3000 kV IMPULSE GENERATOR

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SUMMARY

Characteristics of a 3000 kV Impulse Voltage generator were experimentally determined. Possible wave-shapes with the circuit components furnished by the maker were produced and the actual values for the wave-shapes from oscillograms recorded were compared with those calculated based on formulæ for the wave-shape for the simplified impulse generator circuit. Oscillograms of wave-shapes are given and a method of setting up the impulse generator for producing standard wave-shape is suggested.

INTRODUCTION

The Impulse Voltage Generator rated at 3000 kV output voltage, 50 kWs discharge energy and ·011 μF discharge capacitance was recently installed at the High Voltage Laboratory of the Indian Institute of Science, Bangalore. The equipment includes a high speed cathode-ray oscillograph for the simultaneous viewing and recording of transient waveforms produced by the impulse generator. The equipment comprises most of the modern design features like low generator inductance, flexibility, economy of space, remote control of interstage gaps, remote indication of gap spacing, timer control for ensuring consistent successive impulses, adequate charging equipment, resistors and swamping load capacitors for control of wave-form and other automatic control and safety devices. With the completion of the installation, production of standard wave-shapes required for impulse testing had to be arranged. In the absence of commissioning test data from the manufacturer both on the impulse generator and the cathode-ray oscillograph, tests for transient wave-shapes had to be conducted on the completely assembled equipment.

SELECTION OF CIRCUIT CONSTANTS FOR THE PRODUCTION OF DESIRED WAVE-SHAPES

Symbols Used:

C_g = Surge generator discharge capacitance.

C_L = Load capacitance including test object and measuring sphere gap.

C = Total series capacitance of generator and load.

L_1 = Internal inductance of generator.

R_1 = Inherent internal resistance.
L_2 = External inductance of series resistors and leads.
L_3 = Inductance of test specimen.
L = Total inductance of surge generator discharge circuit.
R_s = Series resistance for wave-front control.
R_d = Divider or tail control resistance.
R_g = Shunt resistance.
R_c = Critical damping resistance.

Fig. 1 gives the schematic diagram of the general impulse generator discharge circuit taking into account all the important factors that affect the wave-shape. The theoretical analysis and the solution of the equations for the impulse voltage that appears across the load involves mathematical treatment. These have been analysed in detail in several technical papers and solution of some of the important circuits have been given by Thomason.[1] But, from practical considerations, the circuit of Fig. 1 could be simplified to that given in Fig. 2 without loss of accuracy in impulse testing of small capacitance loads and this has been adopted as the basic impulse generator circuit.[2] For theoretical considerations, the discharge circuit is treated as consisting of a single capacitor C_g charged to the desired voltage E from the D.C. Charging equipment. For determining the wave-front period for the standard wave, when the final gap breaks down, C_L, the load capacitor is treated as getting charged through R_s and L to the maximum crest value, the effect of R_d being neglected during this period. Whereas for determining the wave-tail duration, C_g and C_L in parallel are considered as discharging through $(R_d + R_s)$. The resistance R_d in parallel with the capacitance

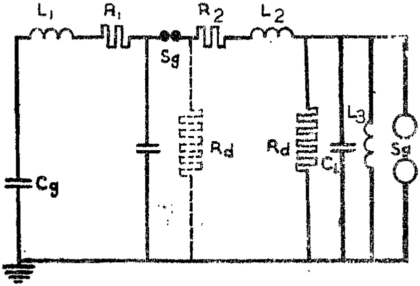

FIG. 1

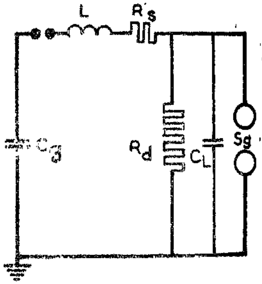

FIG. 2

load serves the dual purpose of shunt resistance for control of duration of the wave and voltage divider for the purpose of measurement of the voltage with the help of the cathode-ray oscillograph. The wave-shapes that are possible with different values for the constants in the basic impulse circuit of Fig. 2 are numerous and are usually designated by the two-point method in terms of the time from zero to maximum value of the voltage and duration to half the crest value.

The main requirements to be met with are:

- (*a*) a smooth wave-shape free from oscillations, especially in the front;
- (*b*) maximum crest value;
- (*c*) minimum wave-front.

The circuit constants to be inserted with a given impulse generator to produce desired waveshapes with specified characteristics have been calculated based on the equations for the standard impulse circuit and charts and curves have been prepared by Thomason[3] in terms of the ratios of C_L/C_g and R_s/R_d and these could be used with advantage for selection of proper circuit constants with any impulse generator and for comparison of results obtained with different impulse generators.

But for the production of standard impulse waves as defined in B.S. 923, A.I.E.E. Standard No. 4 and VDE 0450, 1939, still more simplified formulæ for the nominal wave-front and wave-tail duration are derived from the equations for the voltage wave of the simplified impulse generator circuit based on certain assumptions which are fairly accurate for most practical considerations.

These are according to American practice:

$$T_f = 3R_sC \qquad (1)$$

$$\text{where } \mathbf{C} = \frac{C_g \, . \, C_L}{C_g + C_L}$$

$$T_t = 0{\cdot}7\,(C_g + C_L)\,(R_d + R_s); \qquad (2)$$

[see Appendix III (*b*)]

where T_f is the nominal time in micro-seconds from zero to reach peak value and T_t in micro-seconds is the duration from zero to half the peak value. The above equations are applicable for selecting proper circuit constants provided the circuit is made non-oscillatory by inserting the *critical* value of damping resistance for R_s given by the equation $R_c > 2\sqrt{L/C}$ (L = inductance of discharge circuit), and secondly, the wave to be produced is such that the tail is very large compared with its front as is the case with the standard waves of 1·5/40 and 1/50 designation.

CHARACTERISTICS OF THE 3000 kV IMPULSE GENERATOR

In comparison with the simplified laboratory impulse voltage Generator (Fig. 2) the value for the circuit constants are as follows:—

C_g, the generator discharge capacitance which is a limiting factor for particular generator connection = ·011 μF with 30 capacitors of ·33 μF in series.

R_s, the wave-front control resistor is variable and consists of non-inductive wire-wound resistance cards of different values mounted on wooden racks on the wave shape control frame.

R_g and R_d, the wave tail control and divider resistances are also variable, consisting of resistance cards as above mounted on wooden racks.

C_L = The load capacitor, which can be introduced into the circuit in parallel with the test piece in five steps of capacitance values as shown in Table I, for control of wave-shape and maximum crest value of the voltage applied to the specimen.

L, the inherent inductance of the impulse generator discharge circuit, assumed as being equal to 114 μH including leads as determined experimentally (Appendix I for experimental results).

C_s, the stray capacitance of the impulse generator stack and high voltage leads up to the test piece = 200 $\mu\mu$F. (Appendix II for experimental verification).

R_1, the internal inherent resistance of the capacitor stack = 9·3 Ω.

Z = Surge impedance = 100 Ω.

TABLE I

Load Capacitor ..	No. 1	No. 2	No. 3	No. 4	No. 5
Capacitance in μF ..	0·0031	0·0032	0·0032	0·0032	0·0032
	No. 1 only	2 in series	3 in series	4 in series	5 in series
C_L in microfarads ..	0·0031	0·0016	0·0011	0·0008	0·0006
C in microfarads ..	0·0024	0·0014	0·0010	0·0007	0·0006

(C = total calculated capacitance with C_L in generator discharge circuit, where $C = C_g.C_L/C_g + C_L$, $C_g = 0{\cdot}011\ \mu$F)

The stray capacitance, and inherent resistance being of very low value compared to the other circuit constants, could be neglected for most practical considerations in selecting circuit constants for the production of standard wave-shapes for impulse testing.

EXPERIMENTAL RESULTS

With the above data on the impulse generator experiments were set up to examine the wave-shapes that could be obtained with a variation of the two circuit components *viz.*, C_L, the load capacitance and R_s, the series resistance, the experimental results are given in Table II and corresponding oscillograms of wave-shapes produced with each set-up are given in Figs. 3 to 7.

TABLE II

$C_g = 0{\cdot}011\ \mu F$. Generator connection:—(30 capacitors in series).
C_L as Test Piece. $L = 114\ \mu H$.

1	2	3			4	5	6	7	8	9
No. of Load Capacitors	$R_c = 2\sqrt{L/C}$ Ω	*R_s = series resistance			R_d held constant Ω	Wave-shape by calculation from formulæ (1) and (2) T_f/T_t	Wave-shape produced (measured value from five oscillograms)	Fig. Nos.	C_L/C_g	R_s/R_d
		R_s (Int.) Ω	R_s (Ext.) Ω	Total R_s Ω						
One only ..	436	168	285 (19 cards of 15 ohm each)	453	3880	3·26/40	3·1/40	3	0·28	0·011
Two in series ..	570	168	420 (28 cards of 15 ohm each)	588	3880	2·47/38	2·5/39	4	0·14	0·015
Three in series	675	168	600 (20 cards of 30 ohm each)	768	3880	2·3/39	2·4/38	5	0·096	0·019
Four in series ..	797	168	630 (21 cards of 30 ohm each)	798	3880	1·68/38	1·9/38	6	0·072	0·021
Five in series ..	872	168	720 (24 cards of 30 ohm each)	888	3880	1·59/38	1·6/38	7	0·057	0·022

($R_c = \sqrt{4\,L/C}$, where $C = C_g \cdot C_L / C_g + C_L$. The values of C for each set-up are given in Table I).

* It was observed from the oscillograms of preliminary investigations that the same value of the series resistance R_s for different load capacitance values, resulted in the appearance of a ripple at the peak. Hence, for getting a smooth wave-front the inserted values of R_s was made to exceed the critical values of the resistance, for each set-up.

The calculated values for the wave-front and wave-tail by application of the simplified formulæ (1) and (2) are given in column (5) of Table II, for each value of C_L.

The five oscillograms (Figs. 3 to 7) of each set-up were measured for determining T_f and T_t, in accordance with American practice [see Appendix III (*a*)], and the measured values are given in Column (6) of Table II.

For best results, the series resistance was distributed, part of it inserted within the generator itself. From earlier oscillograms, it was observed that this arrangement had the effect of smoothening the wave-front, especially at the start of the wave.

From the above experimental results, the following observations are verified:—

(i) A smooth wave-front free from oscillations could be obtained by inserting a series resistance greater than the critical damping resistance given by $\sqrt{4L/C}$.

(ii) The circuit constants determined from the simplified formulæ $T_f = 3R_sC$ and $T_t = 0 \cdot 7\,(C_g + C_L)\,(R_d + R_g)$ produce wave-shapes which are in agreement with those obtained from actual oscillograms and could be used for selection of circuit constants for producing a standard wave.

(iii) The characteristics of the wave-shape produced largely depend on the ratio C_L/C_g and R_s/R_d. With the generator capacitance held constant at $0 \cdot 011\,\mu F$, the load capacitance of smaller than $600\,\mu\mu F$ will have to be arranged to produce wave-shapes with nominal wave-front less than $1 \cdot 6\,\mu s$.

(iv) R_d and R_g, the wave-tail control resistors required to give desired duration is fairly independent of changes of load capacitance and the series resistance, required to give desired wave-front, and could be calculated from the simplified formulæ (2) and held constant giving a fixed value for the voltage divider ratio and wave-tail duration.

PRODUCTION OF STANDARD WAVE-SHAPE

It is evident from Table II, that it is not possible to get the standard wave-shape $1 \cdot 5/40$ with the 3000 kV surge generator connection and the 5 load capacitors delivered by the maker.

Based on the above experimental verification of the simplified equations for wave-shape, a standard wave-shape of $1 \cdot 5/40$ was produced from selected circuit constants and the proper value of C_L/C_g. The oscillogram of this wave-shape is given in Fig. 8. The calculations are given in Table III.

In order to obtain a value for the ratio $C_L/C_g < \cdot 05$, with the lowest possible value of $C_L = \cdot 0006$, with all the five load capacitors in series, the

TABLE III

$C_g = 0{\cdot}0165\ \mu$F. Generator connection: 20 capacitors of ·33 μF in series.
$C_L = 0{\cdot}0006\mu$ F, all five in series.

C_g	C_L	C_L/C_g	Series resitaance			R_d	$\frac{R_s}{R_d}$	Wave-shape by calculation	Wave-shape measured from oscillogram (Fig. 8)
			R_s (Int.)	R_s (Ext.)	R_s				
0·0165	0·0006	0·04	9×12=108	750 (25 cards of 30 ohms)	858	2750	0·31	1·49/41	1·5/40

generator connection had to be changed so as to include 20 capacitors in series in ten stages giving a generator discharge capacitance of ·0165 μF.

With the above set-up for standard wave, the impulse generator applies to the test specimen across the load capacitance, the same wave-shape for all values of charge volts. Figs. 9 and 10 show the oscillograms of the above 1·5/40 wave applied to a 10″ suspension insulator to determine its 50% dry impulse flash-over value.

CONCLUSION

The production of standard wave for impulse testing of capacitance loads could be arranged with any impulse generator by choosing the proper value for C_L/C_g and by inserting values of R_s and R_d calculated from the simplified formulæ (1) and (2) for the wave-front and wave-tail duration.

For getting a wave-front of 1 μs with a given generator connection and load capacitance, the value of series resistance has to be further reduced. But, for obtaining a wave-front free from oscillations, the critical damping resistance given by $2\sqrt{L/C}$ has to be inserted as otherwise the resultant voltage wave will be oscillatory with a period given by $T = 2\pi\sqrt{LC}$. The maximum wave-front duration that can be obtained with any surge generator circuit is also limited to one-quarter of the above period, *viz.*, $\pi/2 \times \sqrt{LC}$. Hence minimum wave-front can only be obtained by making L the internal and external inductance as low as possible. The value for the inherent inductance of the generator is limited by the design features, like number of stages, physical arrangements of capacitors, output voltage, etc., and low generator inductance can only be obtained by making the resistors used in the generator discharge circuit for control of wave-shape sufficiently non-inductive.

ACKNOWLEDGMENT

We wish to express our gratitude to Professor Dr. Pfestorf and Mr. D. J. Badkas for their guidance and encouragement.

APPENDIX I

INTERNAL INDUCTANCE MEASUREMENTS

$C_g = 0\cdot 011\,\mu F$, 30 in series, $R_s = 0$

Shunt connected directly between output end of generator and ground.

Fig. No.	Charge* L.S.V.	Shunt Resist. Ω	Time kcps	Wave mm./cycle	Generator Period mm./cycle 1st	2nd	3rd
11	10	0·016	100	31·4	22	22	22
12	10	0·016	100	31	22	22	22

Calcs $T = 2\pi\sqrt{LC}$. $L = T^2/4\pi^2 C$.

From Fig. No. 11

$$\frac{22\text{ mm.}}{31\cdot 4\text{ mm.}} = \frac{x\,\mu s}{10\,\mu s};\quad x,\ \mu s = \frac{22\times 10}{31\cdot 4} = 7\cdot 006\,\mu s.$$

$$\therefore\ L = \frac{(7\cdot 006)^2}{4\times\pi^2\times\cdot 011} = \frac{(7\cdot 006)^2}{\cdot 4341} = 113\cdot 8 \text{ microhenries}$$

or 114 μH including the connection leads.

APPENDIX II

STRAY CAPACITANCE MEASUREMENTS

$C_g = 0\cdot 011\,\mu F$, 30 in series. $R_d = 10{,}380$ ohm, $R_g = \infty$

$C_L = 0\cdot 0$ mfd. $R = 0\cdot 0$ ohm. $L = 114\cdot 0\,\mu H$.

Fig. No.	Charge* L.S.V.	Time kcps	R_s int.	R_s ext.	Damp. Time μs
13	75	500	0·00	0·00	12·5

From Fig. No. 13

Oscillator Period mm./cycle Crest to Crest 1st	2nd	3rd	Wave Period mm./cycle Crest to Crest 1st	2nd	3rd
17·5	17·5	17·5	8	8·5	8

Average = 17·5 mm./cycle. Average = 8 mm./cycle.

Calcs. $T = 2\pi\sqrt{LC}$. $C = T^2/4\pi^2 L$ $T = 2\times 8/17\cdot 5 = 0\cdot 915$

$$C = \frac{(0\cdot 915)^2}{4\pi^2\times 114} = 0\cdot 0002\,\mu fd \text{ or } 200/\text{mmfd.}$$

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* The charge of the condensors was measured on the primary side (L.S.V.) of the transformer.

APPENDIX III

(*a*) MEASUREMENT OF WAVE-SHAPE FROM OSCILLOGRAMS[4]

Sample Calcs.

Fig. No.	AX_1	DX_3	CX_2	O_1X_1
14	29	8·7	26·1	4·5 mm.

From Timing Wave : $10\,\mu s = 27\cdot6$ mm.

$$\therefore\quad T_f = \frac{4\cdot5\times10}{27\cdot6} = 1\cdot63\,\mu s;\quad T_t = \frac{110}{27\cdot6} = 39\,\mu s.$$

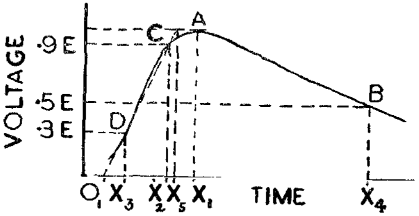

FIG. 14

(*b*) In determining the wave-front duration for a standard wave, the wave-tail resistance R_d could be neglected and with critical damping resistance inserted for the series resistance, the equation[5] for the voltage across load is given by

$$v = C/C_L.E\,(1 - e^{-t/CR}),$$

where v = voltage at any instant during the wave-front period

$C = C_g \cdot C_L / C_g + C_L$

E = Maximum voltage to which the surge generator capacitors are charged prior to discharge.

$C/C_L = C_g.C_L/(C_g+C_L)\,C_L$ is equal to unity when C_L is small compared with C_g.

$$\therefore\quad v = E\,(1 - e^{-t/CR}) \tag{i}$$

Let t_1 be the time for the voltage to reach from zero to 90% of full value

t_2 be „ „ „ from zero to 30% of full value

t_f' be the time interval for the voltage to reach from 30% to 90% of peak value

Substituting the values of v/E in equation (i)

$$t_2/CR = 2\cdot3 \text{ or } t_2 = 2\cdot3\ CR.$$

$$\text{and } t_1/CR = 0\cdot3 \text{ or } t_1 = 0\cdot3\ CR.$$

$$t_f' = (t_2 - t_1) = 2\ CR. \qquad \text{(ii)}$$

T_f (Nominal wavefront duration for the standard wave as per American practice) $= 1\cdot5\, t_f' = 3CR$ (iii)

In determining T_t, Time to half value, $(C_g + C_L)$ in parallel is considered as discharging through $(R_d + R_s)$

$\therefore$ $V = Ee^{-t/CR}$, where C is equal to $(C_g + C_L)$ and R is equal to $(R_d + R_s)$ (iv)

Substituting $V/E = 0\cdot5$, $t = T_t = 0\cdot7$ CR

in equation (iv)

$\therefore$ T_t = Time in μs to reach half the peak value

$$= 0\cdot7\,(C_g + C_L)\,(R_d + R_s) \qquad \text{(v)}$$

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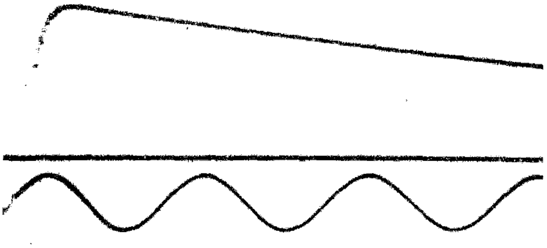

FIG. 3. Oscillogram for 3·1/40 wave

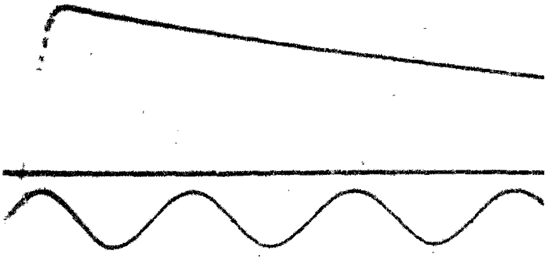

FIG. 4. Oscillogram for 2·5/39 wave

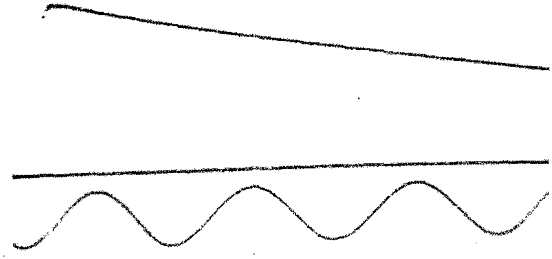

FIG. 5. Oscillogram for 2·4/38 wave

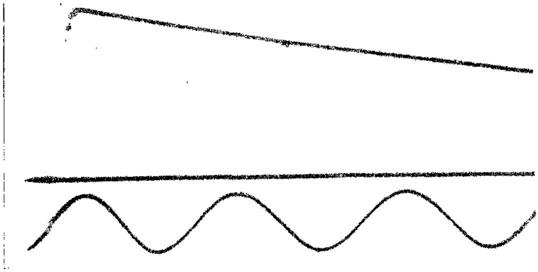

FIG. 6. Oscillogram for 1·9/38 wave

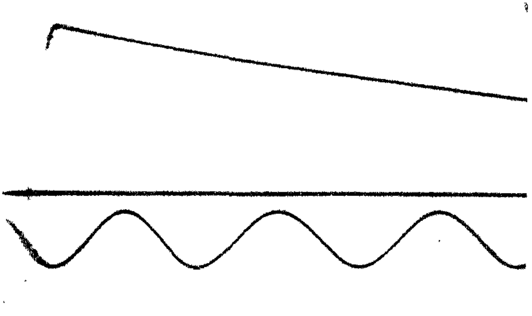

FIG. 7. Oscillogram for 1·6/38 wave

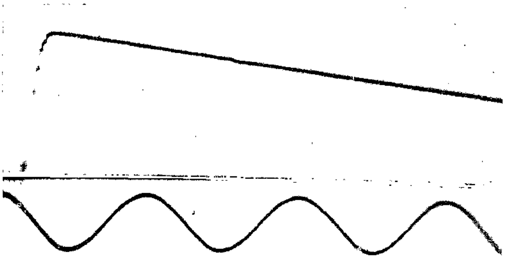

FIG. 8. Oscillogram for standard 1·5/40 wave

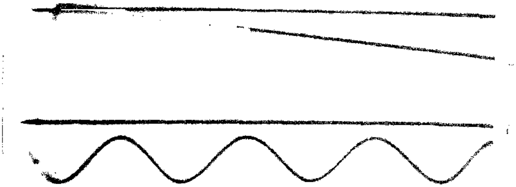

FIG. 9. Oscillogram for standard wave with test specimen (10″ Disc type Insulator)

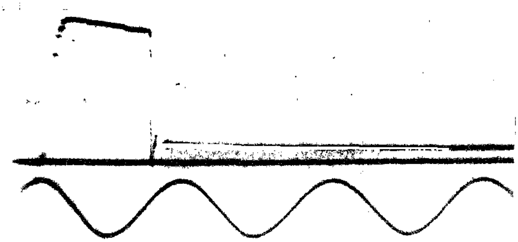

FIG. 10. Oscillogram for chopped wave

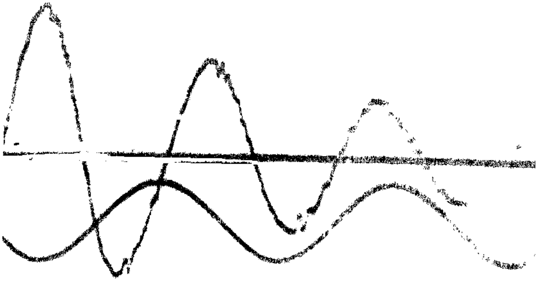

FIG. 11. Oscillogram for the determination of the Generator Inductance

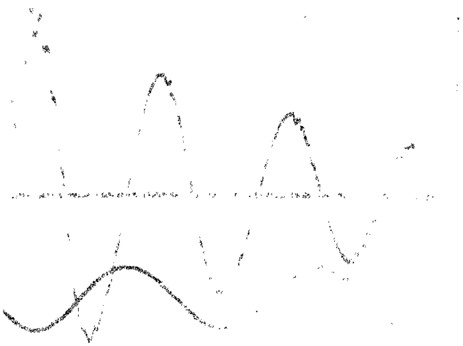

FIG. 12. Oscillogram for the determination of the Generator Inductance

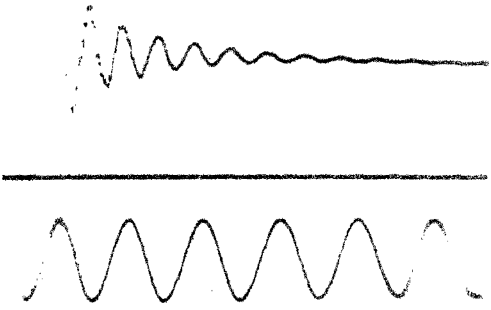

FIG. 13. Oscillogram for the determination of stray capacitance