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 formulae 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 0.011 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:

- \( C_r \) = 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.
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. 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. For theoretical considerations, the discharge circuit is treated as consisting of a single capacitor \( C_p \) 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, \( C_p \) and \( C_L \) in parallel are considered as discharging through \( (R_d + R_s) \). The resistance \( R_d \) in parallel with the capacitance...
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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\(^2\) in terms of the ratios of \(C_L/C_L\) and \(R_d/R_d\) 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 formulae 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:

\[T_f = 3R_f C\]  
\[(1)\]

\[T_x = 0.7(C_g + C_L) (R_d + R_d);\]  
\[(2)\]

[see Appendix III (b)]

where \(T_f\) is the nominal time in micro-seconds from zero to reach peak value and \(T_x\) 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 \(R_x\) given by the equation \(R_x > 2\sqrt{L/C}\) (\(L = \) 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 \(1 \cdot 5/40\) 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 = \(0.011 \mu F\) with 30 capacitors of \(0.33 \mu F\) in series.
- \(R_w\), 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.
- \(R_w\) 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 1, 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 \(114 \mu H\) including leads as determined experimentally (Appendix I for experimental results).
- \(C_n\), the stray capacitance of the impulse generator stack and high voltage leads up to the test piece = \(200 \mu F\). (Appendix II for experimental verification).
- \(R_h\), the internal inherent resistance of the capacitor stack = \(9.3 \Omega\).
- \(Z\) = Surge impedance = \(100 \Omega\).

**Table 1**

<table>
<thead>
<tr>
<th>Load Capacitor</th>
<th>..</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
<th>No. 4</th>
<th>No. 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance in (\mu F)</td>
<td>..</td>
<td>0.0031</td>
<td>0.0032</td>
<td>0.0032</td>
<td>0.0032</td>
<td>0.0032</td>
</tr>
<tr>
<td></td>
<td>No. 1 only</td>
<td>2 in series</td>
<td>3 in series</td>
<td>4 in series</td>
<td>5 in series</td>
<td></td>
</tr>
<tr>
<td>(C_L) in microfarads</td>
<td>..</td>
<td>0.0031</td>
<td>0.0016</td>
<td>0.0011</td>
<td>0.0008</td>
<td>0.0006</td>
</tr>
<tr>
<td>(C) in microfarads</td>
<td>..</td>
<td>0.0024</td>
<td>0.0014</td>
<td>0.0010</td>
<td>0.0007</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

(\(C = \text{total calculated capacitance with } C_L\) in generator discharge circuit, where 
\(C = C_g\cdot C_L/C_g + C_L, C_g = 0.011 \mu F\))
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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

<table>
<thead>
<tr>
<th>No. of Load Capacitors</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \frac{2\sqrt{L/C}}{\Omega} )</td>
<td>* ( R_s ) = series resistance</td>
<td>( R_s ) ( \Omega ) ( \text{Int.} )</td>
<td>( R_s ) ( \Omega ) ( \text{Ext.} )</td>
<td>Total ( R_s ) ( \Omega )</td>
<td>( R_d ) ( \Omega ) = constant</td>
<td>Wave-shape by formulae (1) and (2)</td>
<td>Wave-shape produced from measured oscillograms</td>
</tr>
<tr>
<td>One only</td>
<td>436</td>
<td>168</td>
<td>258</td>
<td>453</td>
<td>3880</td>
<td>3·26/40</td>
<td>3·1/40</td>
<td>3</td>
<td>0·29</td>
</tr>
<tr>
<td>Two in series</td>
<td>570</td>
<td>168</td>
<td>420</td>
<td>588</td>
<td>3880</td>
<td>2·47/38</td>
<td>2·5/39</td>
<td>4</td>
<td>0·14</td>
</tr>
<tr>
<td>Three in series</td>
<td>675</td>
<td>168</td>
<td>620</td>
<td>768</td>
<td>3880</td>
<td>2·3/59</td>
<td>2·4/38</td>
<td>5</td>
<td>0·096</td>
</tr>
<tr>
<td>Four in series</td>
<td>707</td>
<td>168</td>
<td>720</td>
<td>798</td>
<td>3880</td>
<td>1·68/38</td>
<td>1·9/38</td>
<td>6</td>
<td>0·072</td>
</tr>
<tr>
<td>Five in series</td>
<td>872</td>
<td>168</td>
<td>768</td>
<td>888</td>
<td>3880</td>
<td>1·50/38</td>
<td>1·6/38</td>
<td>7</td>
<td>0·057</td>
</tr>
</tbody>
</table>

\( R_s = \sqrt{L/C} \), where \( C = C_L + C_E + C \). 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 formulae (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 $T_i$, 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 formula $T_f = 3R_sC$ and $T_i = 0.7 \left( C_{r'} \right) (R_s + R_j)$ 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 $R_s/R_j$. With the generator capacitance held constant at $0.011 \mu F$, the load capacitance of smaller than $600 \mu F$ will have to be arranged to produce wave-shapes with nominal wave-front less than $1.6 \mu s$.

(iv) $R_s$ and $R_j$, 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 formula (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 $1.5/40$ 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 $1.5/40$ 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 $C_L/C_g < 0.05$, with the lowest possible value of $C_L = 0.0006$, with all the five load capacitors in series, the
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Table III

<table>
<thead>
<tr>
<th>$C_g$</th>
<th>$C_L$</th>
<th>$C_L/C_g$</th>
<th>$R_s$ (Int.)</th>
<th>$R_f$ (Ext.)</th>
<th>$R_f$</th>
<th>$R_s$</th>
<th>$R_d$</th>
<th>Wave-shape by calculation</th>
<th>Wave-shape measured from oscillogram (Fig. 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0165</td>
<td>0.0006</td>
<td>0.04</td>
<td>9 x 12 = 108</td>
<td>750</td>
<td>858</td>
<td>2750</td>
<td>0.31</td>
<td>1.49/41</td>
<td>1.5/40</td>
</tr>
</tbody>
</table>

generator connection had to be changed so as to include 20 capacitors in series in ten stages giving a generator discharge capacitance of 0.0165 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 $R_f$ calculated from the simplified formulae (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

\[ C_g = 0.011 \mu F, \ 30 \text{ in series, } R_s = 0 \]

Shunt connected directly between output end of generator and ground.

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Charge* L.S.V.</th>
<th>Shunt Resist.</th>
<th>Time kcps</th>
<th>Wave mm./cycle [ \omega ]</th>
<th>Generator Period mm./cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>10</td>
<td>0.016</td>
<td>100</td>
<td>31.4</td>
<td>22  22  22</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>0.016</td>
<td>100</td>
<td>31</td>
<td>22  22  22</td>
</tr>
</tbody>
</table>

Cals. \[ T = 2\pi \sqrt{LC}. \]

\[ L = \frac{T^2}{4\pi^2C}. \]

From Fig. No. 11

\[ \text{22 mm.} = \frac{X_{\mu s}}{10 \mu s}; \quad x, \mu s = \frac{22 \times 10}{31.4} = 7.006 \mu s. \]

\[ \therefore L = \frac{(7.006)^2}{4 \times \pi^2 \times 0.011} = \frac{(7.006)^2}{0.4341} = 113.8 \text{ microhenries} \]

or 114 \( \mu \text{H} \) including the connection leads.

APPENDIX II

STRAY CAPACITANCE MEASUREMENTS

\[ C_g = 0.011 \mu F, \ 30 \text{ in series. } R_d = 10,380 \text{ ohm, } R_s = \infty \]

\[ C_L = 0.0 \text{ mfd. } R = 0.0 \text{ ohm. } L = 114.0 \mu \text{H}. \]

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Charge* L.S.V.</th>
<th>Time kcps</th>
<th>[ R_s ]</th>
<th>Damp. Time [ \mu s ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>75</td>
<td>500</td>
<td>0.00</td>
<td>0.00  12.5</td>
</tr>
</tbody>
</table>

From Fig. No. 13

Oscillator Period

| Wave Period |
| mm./cycle | Crest to Crest |
| 1st | 2nd | 3rd |
| 17.5 | 17.5 | 17.5 |

Average = 17.5 mm./cycle.

Cals. \[ T = 2\pi \sqrt{LC}. \]

\[ C = \frac{T^2}{4\pi^2L} = 0.0002 \mu \text{fd or 200/mmfd.} \]

---

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

(a) Measurement of Wave-Shape from Oscillograms

Sample Data.

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>AX₁</th>
<th>DX₂</th>
<th>CX₃</th>
<th>O₁X₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>29</td>
<td>8.7</td>
<td>26.1</td>
<td>4.5mm</td>
</tr>
</tbody>
</table>

From Timing Wave: \(10 \mu s = 27.6 \text{ mm.}\)

\[ T_f = \frac{4.5 \times 10}{27.6} = 1.63 \mu s; \quad T_r = \frac{110}{27.6} = 39 \mu s. \]

\[ v = \frac{C}{C_L} E (1 - e^{-\frac{t}{T_f}}), \]

where \(v = \text{voltage at any instant during the wave-front period}\)

\[ C = C_g \cdot C_L / C_g + C_L \]

\(E = \text{Maximum voltage to which the surge generator capacitors are charged prior to discharge.}\)

\[ C / C_L = C_g \cdot C_L / (C_g + C_L) \]

\(C_L\) is equal to unity when \(C_L\) is small compared with \(C_g\).

\[ v = E (1 - e^{-\frac{t}{T_f}}), \quad (i) \]

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)

\[
{t_2}/{CR} = 2 \cdot 3 \text{ or } t_2 = 2 \cdot 3 CR.
\]

and \( {t_1}/{CR} = 0 \cdot 3 \text{ or } t_1 = 0 \cdot 3 CR. \)

\[
{t_1}' = (t_2 - t_1) = 2 CR.
\]  \hspace{1cm} \text{(ii)}

\( T_f \) (Nominal wavefront duration for the standard wave as per American practice) = 1 \cdot 5 {t_1}' = 3CR \hspace{1cm} \text{(iii)}

In determining \( T_f \), Time to half value, \((C_x + C_1)\) in parallel is considered as discharging through \((R_{rd} + R)\)

\[
\therefore \quad V = Ee^{t/CR}, \text{ where } C = (C_x + C_1) \text{ and } R = (R_{rd} + R).
\]  \hspace{1cm} \text{(iv)}

Substituting \( V/E = 0 \cdot 5 \), \( t = T_f = 0 \cdot 7 CR \) in equation (iv)

\[
\therefore \quad T_f = \text{Time in } \mu s \text{ to reach half the peak value}
\]

\[
= 0 \cdot 7 (C_x + C_1) (R_{rd} + R).
\]  \hspace{1cm} \text{(v)}

**REFERENCES**

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
Oscillogram for the determination of the Generator Inductance

Oscillogram for the determination of the Generator Inductance

Oscillogram for the determination of the stray capacitance