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Simulation of Impulse Voltage Generator and Impulse Testing of Insulator using MATLAB Simulink

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Abstract. The main objectives of this work are of two folds: the first is the design of impulse voltage generator and impulse testing of a standard disc type insulator experimentally. The second is the development of MATLAB Simulink model of the above mentioned experimental setup. Investigation shows that this software is very efficient in studying the effect of parameter changes in the design to obtain the desired impulse voltages and wave shapes from an impulse voltage generator for high voltage applications.

Keywords: lightning and switching impulses, impulse voltage generator, MATLAB Simulink

1 Introduction

International Electro technical Commission (IEC) has specified that the insulation of transmission line and other equipment's should withstand standard lightning impulse voltage of wave shape $1.2/50\mu s$ and for higher voltages (220 kV and above) it should withstand standard switching impulse voltage of wave shape $250/2500\mu s$[5].

In the design or use of impulse voltage generators for research or testing, it is required to evaluate the time variation of output voltage, the nominal front and tail times and the voltage efficiency for given circuit parameters. Also, it needs to predict circuit parameters for producing a given wave shape, with a given source and loading conditions. The loading can be inductive or capacitive. The wave shapes to be produced may be standard impulse, steep fronted impulse, short tailed impulse or steep front short tailed impulse.

Expressions and curves have been already developed to predict the parameters of impulse voltage generator circuits required to reproduce the wave forms of required shape for the testing of transformers[1]. An analysis of standard Marx circuit, with an inductance in series with the tail resistance for the production of short tailed impulses was done by Carrus [2]. An algorithm workable in a personal computer to evaluate the time variation of the output voltage, nominal front and tail times and voltage efficiency for given circuit parameters or to predict the circuit parameters for given wave shape, source and loading conditions was reported in [15].

After performing an experimental investigation to evaluate the influence of tail resistance and tail inductance in the characteristic parameters of the impulses, provision of an analytical criterion is available for choosing the most suitable inductance value to be combined with a given resistance in order to generate the desired waves[3]. Methods to be followed to determine parameters and indicate practical criteria which facilitate generation of wave shape of the above type have been also shown in [3]. Studies of transient disturbances on a transmission system have shown that lightning and switching operations are followed by a traveling wave of

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a steep wave front. This type of impulse may result in the breakdown of the insulation system in power equipment's. Generation of impulse voltages in a test laboratory becomes, therefore, one of the standard techniques for testing the breakdown strength of electrical insulation. In high voltage engineering, assembling the actual circuit might be very bulky, time consuming and costly, while for the design, calculation technique could be complicated and may involve a lot of simplifications.

The analysis, design and practical implementation of impulse voltage generator without computer simulation is extremely laborious, time consuming and expensive. Various types of software like SPICE (Simulation Program with Integrated Circuit Emphasis) has been used to predict the performance of impulse voltage generator[6, 9, 10, 14]. Although SPICE can analyze generator circuits, it is less well suited for dynamic analysis and design, which Simulink can handle with ease. However SPICE is very slow and is not practical for the design purposes. The step-by-step modeling of an impulse voltage generator, used for the testing of high voltage power transmission and distribution equipment's, has been carried out and the performance evaluated from the MATLAB package with its Simulink tool box suitable for dynamic system simulation. The system is first represented by a set of mathematical equations; the derived equations are modeled with standard blocks available in Simulink and the complete system is then simulated[4, 7, 8, 11–13].

In this work, a high voltage impulse testing is conducted on standard disc type insulator using 100 kV single stage impulse generator in the high voltage laboratory and the above mentioned set up is simulated with MATLAB SIMULINK and the test results are compared.

2 MATLAB Simulink

Simulink is an extension of MATLAB is specifically designed for modelling, analyzing and simulating a wide variety of dynamic systems[4, 7, 8, 11–13]. Simulink provides a graphical user interface for constructing block diagram models using drag and drop operations. A system is configured in terms of block diagram representation from a library of standard components. A system in block diagram representation is built easy and the simulation results are displayed quickly. Simulation algorithms and parameters can be changed in the middle of a simulation with intuitive results, thus providing the user with a ready access learning tool for simulating many of the operational problems found in the real world. Generally Simulink provides an open architecture that allows extending the simulation environment. In MATLAB Simulink library, power system block set is used to simulate the setup. The speed and the capability of Simulink in simulating dynamic systems were the attraction to choose it for modelling impulse voltage generator circuit in this work.

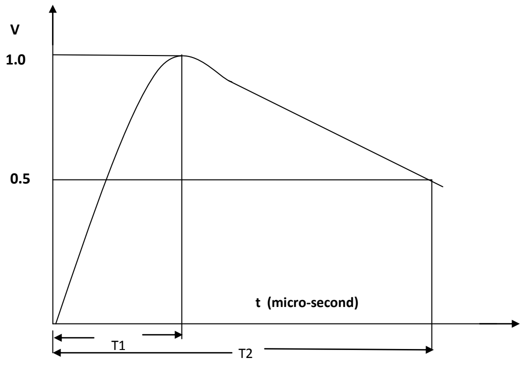

Fig. 1. Standard $1.2 \times 50\mu s$ wave shape

3 Impulse voltage generators

An impulse generator essentially consists of a capacitor which is charged to the required voltage and discharged through a circuit. The waveform, Fig. 1, is the standard $1.2/50\mu s$ duration with the peak voltage reached in $1.2\mu s$ $(T1)$ and the tail of the wave decaying to a level of 50 percent of the peak in $50\mu s$ $(T2)$. The circuit parameters can be adjusted to give an impulse voltage of the desired shape. Basic circuit of a single stage impulse generator is shown in Fig. 2, where the capacitor C_s is charged from a dc source until the spark gap G breaks down. The voltage is then impressed upon the object under test of capacitance C_b. The wave shaping resistors R_d and R_e control the front and tail of the impulse voltage available across C_b respectively. Overall, the wave shape is determined by the values of the generator capacitance (C_s) and the load capacitance (C_b), and the wave control resistances R_d and R_e.

For a multistage generator, a group of capacitors are charged in parallel and discharged in series. The switch over of capacitors from a parallel connection to series connection occurs automatically when the intermediate spark gap breaks down after the capacitors are charged to the required potential V_0. The voltage at the generator terminal is $v(t)$ and is equal to $n\ V_0$ where $'n'$ is the number of stages.

The output voltage waveform can be defined by

$$v(t) = \frac{V_0}{C_b R_d(\alpha - \beta)}(e^{-\alpha t} - e^{-\beta t}), \tag{1}$$

where, $v(t)$ instantaneous output voltage, V_o DC charging voltage, α, β roots of the characteristics equation, which depends on the parameters of the generator.

$$\alpha = \frac{1}{R_d C_b}, \quad \beta = \frac{1}{R_e C_z}.$$

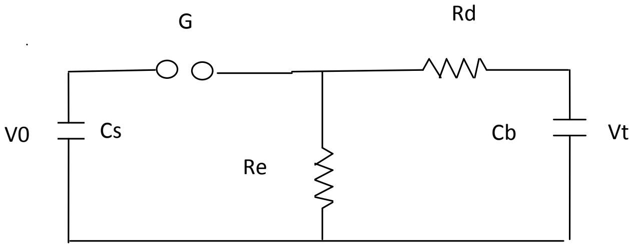

Fig. 2. Basic circuit of single stage impulse generator

The exact wave shape, however, will be affected by the line inductance that comes from the physical dimensions of the circuit. Analysis using Simulink could become very useful in the proper selection of such components before even assembling them together.

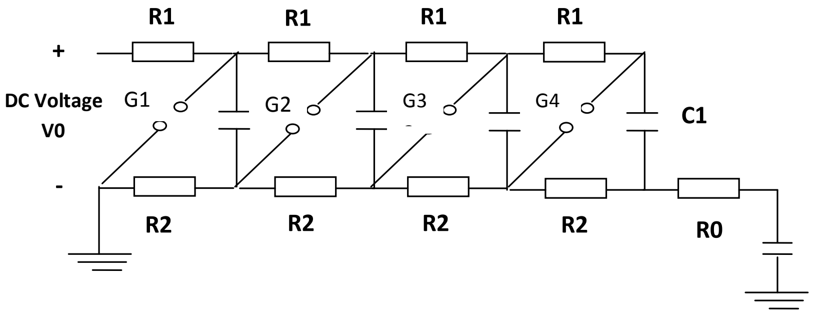

Fig. 3. Equivalent circuit of Multi-stage impulse generator

3.1 Analysis of impulse voltage generator

The equivalent circuit of a high voltage multi-stage impulse voltage generator is shown in Figs. 3 and 4 gives the circuit of a multi-stage impulse voltage generator. Referring to Figs. 3 and 4, the operation of the multi-stage generator can be described as follows. All capacitors, one in each stage, are charged to a voltage V relative to ground. The bottom sphere gap is triggered by voltage injection and breaks down, discharging that stage capacitor. Subsequently, the remaining stage gaps also break down, discharging each stage capacitor. The result is a cumulative swing in voltage from zero to nV, where n is the number of stages in the Marx generator. The sphere gaps act as switches. Once the first gap breaks down, the capacitor swings from V to zero, see point A Fig. 4. This represents a swing of potential of $-V$ and at this instant the voltage at point C is $-V$. This results in a potential difference of $2V$ across the second gap and causing it to break down. This action continues across each stage gap. The first stage sphere gap, in effect, is a trigger for applying the peak voltage to the load. As part of the impulse generator, the load capacitor is large enough to overcome the effects of the stray capacitance to allow the simultaneous gap breakdowns to occur.

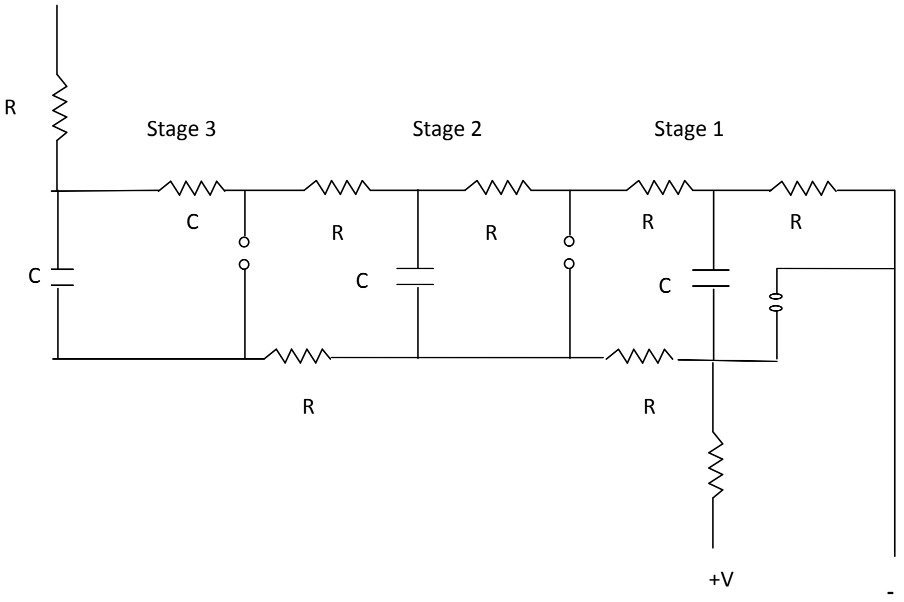

Fig. 4. Multi-stage impulse generator working

Fig. 5. Impulse voltage generator

Fig. 6. Experimental setup for flash over testing of disc insulator

The system equations may be put in the following form.

$$\frac{\mathrm{d}V_0}{\mathrm{d}t} = \frac{V_0}{C_z R_e} + \frac{i_0}{C_z},$$

$$\frac{\mathrm{d}V_0}{\mathrm{d}t} = \frac{i_0}{C_b},$$

$$V_0(t_0+\delta t_0) = v(t_0) + \delta t\left(\frac{\mathrm{d}V_0}{\mathrm{d}t}\right)_{t=t_0},$$
$$V_0(t_0+\delta t_0) = v(t_0) + \delta t\left(\frac{\mathrm{d}v(t)}{\mathrm{d}t}\right)_{t=t_0}. \tag{2}$$

Values of R_d, R_e, C_z and C_b can be obtained by using the above equations.

3.2 Problem associated with impulse generator

In the case of a 15 stages 3MV multi-stage, the capacitors are charged to 200 kV from a regulator and charging supply section. After the capacitors are charged, the first gap G_1, is triggered from a pulse triggering circuit, which in turn causes a breakdown of all other gaps. To obtain the desired waveform, the choice of R_d and R_e is critical. Changing these high voltage resistors in the laboratory can be inconvenient as the components are too bulky and the processes are time consuming. Also, the generator has to be triggered each time to obtain the desired output waveform, which at times could become risky for the personnel involved. Hence, modelling of the generator using Simulink would be a remedy for the above problems.

3.3 Statement of the problem

The problem to be solved in this work is to create a simulation circuit that has an output wave shape equivalent to that of an Impulse Generator. An existing 100kV Impulse Generator at the institution will be utilized to generate the laboratory testing results. Several different voltage levels will be tested and measured from the laboratory equipment setup. The Impulse Generator setup is utilized for impulse testing of Medium Voltage Switchgear up to and including 250kV levels. The testing wave shape is $1.2/50\mu s$, with the peak voltage reached in $1.2\mu s$. Several iterations may be required to tune the value of stray capacitance in the simulation to more closely match the Impulse Generator generated wave shape. Also, the value for the initial charge on the stage capacitors is the same as that used in the actual impulse generator. These final simulation values will be compared with the base wave shape details.

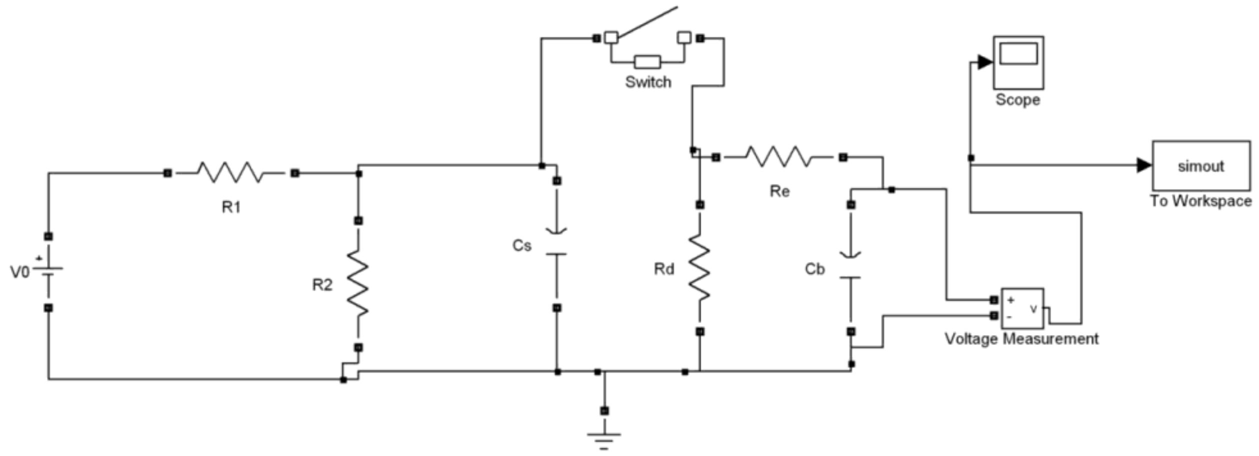

Fig. 7. MATLAB Simulink model of a single stage-impulse generator

4 Experimental testing setup

The impulse generator used in the testing was a single stage generator resulting in a peak capability of 140kV. An impulse generator has two resistors per stage. The front resistor allows the front of the wave to reach peak in the desired time. The second resistor refers to as the tail resistance, is required for the half voltage level at the end of the tail wave shape. Experimental setup for impulse voltage generator and flash over testing of disc insulator is shown in Fig. 5 and 6. In this setup, the front stage resistor value is $245k\Omega$. The tail stage resistor value is 1200Ω. The experiment involves the use of very high voltages. But the available supply voltage is only $230V$. It has to be stepped up to the desired value by using a step up transformer. A $220/100kV$ step up transformer is used. The AC voltage is rectified by means of two diode rectifiers rated $20mA$, $100k\Omega$ and $20mA$, $400k\Omega$. The dc voltage is applied across the source capacitance $(C_s = 5000pf)$. The load capacitance (C_b) is $1000pf$. Spark gap comes across two spheres of diameter $25cm$, one of them is fixed. The other sphere is connected to calibrated metal rod which can be moved to vary the distance between the spheres. One end of the source capacitance is connected to DC volt meter. Other end is grounded. Across the load capacitance (Cb) impulse voltmeter is connected. An earth electrode is provided for discharging. The laboratory room is provided with electrostatic protection by enclosing it in a wire mesh which is connected directly to earth. The impulse flash over test on $11kv$ disc insulator is also conducted. Experimental results are tabulated in Tab. 1.

Table 1. Experimental observations

Sphere gap in cm	DC voltage in kV	Impulse flash over voltage in kV
3.6	78	70
3.8	80	72
4.4	96	87
4.7	98	88
5.1	104	94

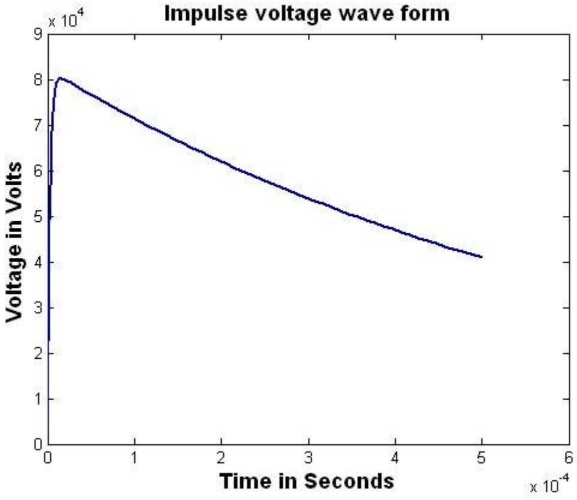

Fig. 8. $R_e = r_1, R_d = r_2$

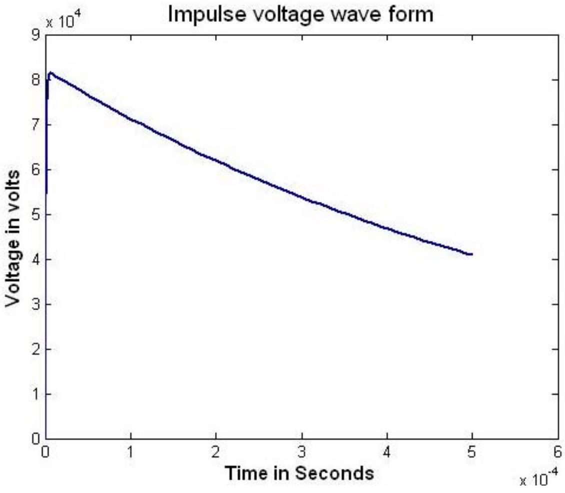

Fig. 9. $R_e = r_3, R_d = r_4$

5 MATLAB Simulink modelling of the impulse generator

Impulse voltage generator can be developed by MATLAB Simulink with standard blocks available in Simulink as shown in Fig. 7. The single-stage impulse voltage generator is simulated with the software. The stage sphere gaps were simulated by the use of switches, as shown. In the case of multistage system, each of the stage capacitors was given an initial charge voltage value, which is equal to 1/n of the total kV test voltage. The values of front and tail resistors, as well as the stage capacitors, are the same as used in the actual impulse generator. The impulse waveforms generated from MATLAB Simulink model with different front and tail resistors is shown in Figs. 8 $\sim$ 10. Flash over testing of disc insulator is also simulated using MATLAB Simulink and the result is shown in Fig. 11.

In a large number of applications, the rise time of the impulse voltage is rather important and therefore, it becomes necessary to determine the effect of wave shaping control elements on the voltage waveform. Different desired outputs can be obtained simply by changing the values of capacitance and resistance. The dependence of the wavefront on the front resistor and load capacitance is observed using Simulink. A comparison between the waveforms obtained using MATLAB Simulink with those derived by methods already reported in literatures[4, 7, 8, 10–13] for the generation of standard, steep front and short tailed impulse waveforms confirmed the validity of the Simulink program.

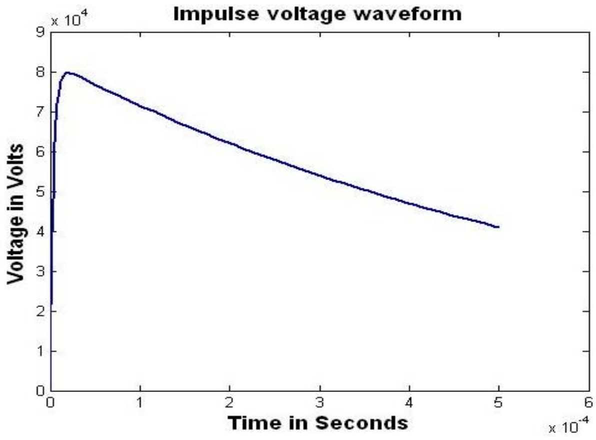

Fig. 10. $R_e = r_5$, $R_d = r_6$

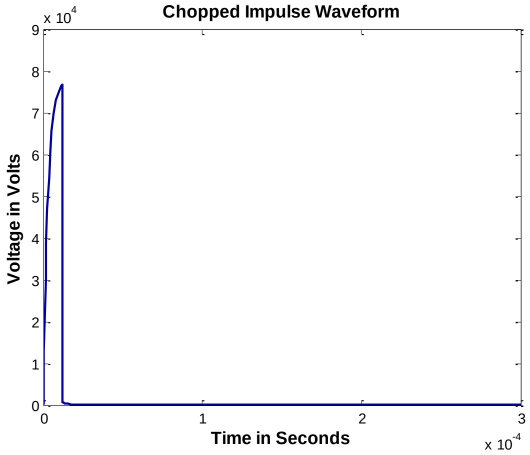

Fig. 11. Simulated Flash over test output

6 Conclusions

A real model of a standard impulse voltage generator was developed using MATLAB Simulink. This modeling technique could be extended to some other applications in the area of power electronics, power systems, etc. The simulation circuit closely approximated the actual base impulse generator. The resistance value of the stage front resistor also has an impact on the time to peak and, in actual impulse generators; this value is adjusted to correct the time to be in tolerance. The value of the actual tail resistor was used in the simulation and resulted in the wave tail time (T_2) within tolerance. The peak voltage also was well within tolerance and closely approximated the base impulse generator. The initial charge of each stage capacitor is the most common method of adjusting the actual peak test output voltage. The simulation circuit resulted in close to actual impulse generator $1.2 \times 50 \mu s$ wave shape for the test voltages.

The major problem observed in high voltage field is the testing of HV equipment in the lab. The voltage ratings of the different equipments are different there by it requires different rating high voltage impulse generators and the associated equipments. It is very difficult to setup those practically. In this paper it is found that the above complication can reduced by means of efficient simulation software. This can also save expense and time by not actually performing test impulse attempts.

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