Development of Virtual Impulse Laboratory

Prashant Kr Agrawal, Chandan, N. K. Kishore

Department of Electrical Engineering
Indian Institute of Technology
Kharagpur-721302, India.
E-mail: prashantiitkgp@yahoo.co.in

Abstract

Natural phenomena such as lightning result in transient overvoltages and overcurrents thus interrupting the power supply. To avoid this, an analysis of impulse voltages and currents is a must. Apart from existing high voltage laboratories, a need was felt to develop a virtual laboratory which being user-interactive will have facilities for generating virtual impulse voltages and currents. Hence an interactive web based laboratory is introduced now to determine the impulse generator settings in order to virtually realize standard impulse voltages and currents. This solution also aims to develop software that enables the user to pre-select the values of circuit elements that will be required to generate impulse voltages and currents for test purposes. These impulses have to meet a voltage-time-curve with certain tolerances according to IEC 60060-1 [7]. This application makes the software useful for impulse testing of power apparatus.

The input is fed by the user using the web based interface. These values sent by the client machine are then received by the server. The server processes the input data using the software which runs using programs in Java and PHP. If need arises to access the available database, developed using MSSQL, the database is accessed. The output data is then sent to the client machine and is displayed in Java applet on the user's browser.

1   Introduction

An uninterrupted supply of electricity is of supreme importance in all our activities. Transient overvoltages and overcurrents due to lightning and switching surges are the main causes of interruption of the continuous supply of electricity by causing a breakdown of insulation of the transmission lines and various power apparatus thus causing severe damage to these equipments. So power apparatuses are generally required to undergo several insulation tests to demonstrate that the equipment fulfils the specified requirements and quality standards [1]. High voltage laboratories are an essential requirement for making acceptance tests for the equipment that go into operation in the high voltage transmission systems. In addition, they are also used in the development work on the equipment for conducting research, and for planning to ensure economical and reliable extra high voltage transmission systems.

The cost of setting up a real high voltage laboratory and maintaining it is quite high. Some of the main facilities provided in a high voltage laboratory are to carry out impulse voltage and impulse current tests on various power equipments like transformers, power cables, surge arresters etc. The paper describes an attempt to develop a platform independent web based Virtual Impulse Laboratory (VIL) which simulates these tests. VIL demonstrates the use of web tools in high voltage engineering. It will serve as a good tool for teaching and enable a student to understand the influence of the circuit parameters on the waveshape. It can also serve as a guide for the testing engineer to arrive at the values of the generator parameters for various types of loads. References [6, 10] indicate efforts made in developing such laboratories. Major improvements are in the present work includes all possible impulse tests i.e. impulse voltages for Lightning overvoltages and switching overvoltages, impulse currents and rectangular currents. It is more enhanced by way of inclusion of various power apparatus details. Above all in its final form laboratory envisages an online user help.

2   Fundamentals

A standard impulse waveshape can be represented as a double exponential wave [1] defined by the equation,

$$V = V_o (e^{-at} - e^{-bt})$$

A general impulse waveshape is shown in Fig. 1. The standard parameters characterizing the waveshape [8] are -

Front time $T_f = 1.25 (t_{0.9} - t_{0.1})$
Tail time $T_t = t_{0.5}$ (on the falling side)
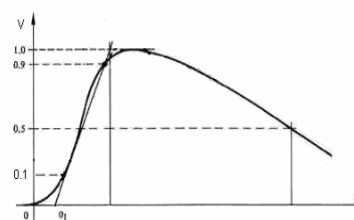Peak voltage (or current) $= V_p$ (or I_p)

Fig. 1. General shape of a lightning impulse voltage

The time parameters and tolerances for some standard impulse waves [8] are given in Table I.

Type of Impulse	T_f (us)	T_t (us)
LI voltage	$1.2 \pm 30\%$	$50 \pm 20\%$
SI voltage	$250 \pm 30\%$	$2500 \pm 20\%$
Impulse Current	$4.0 \pm 10\%$	$10.0 \pm 10\%$
Impulse Current	$8.0 \pm 10\%$	$20.0 \pm 10\%$

Table 1. Standard impulses and their time parameters with tolerances

A double exponential waveshape can be generated by having a circuit with energy storage elements with independent control for rising portion and falling portion of the wave. Marx circuit is used for generating high impulse voltages. The schematic diagram of Marx circuit is shown in Fig. 2. The basic principle of operation of the Marx circuit is that the capacitors are charged in parallel and discharged in series. Hence a very high voltage can be obtained when the impulse generator gets discharged. Here, the front resistors and the discharge resistors are distributed along each stage. Triggered sphere gaps are used as switches to connect the parallely charged capacitors in series. The capacitors are charged in parallel from a dc source. On firing the lowest gap, stages 1 and 2 get connected in series. Hence the individual voltages across the stages 1 and 2 appear as a sum across the next gap, thereby triggering it and thus connecting all the stages in series. And hence an impulse voltage is obtained across the load.
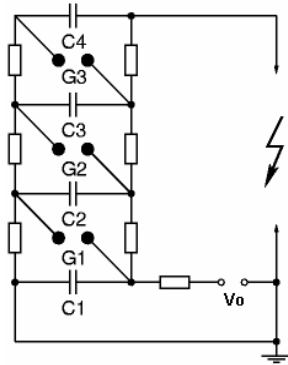

Fig. 2. Schematic diagram of Marx circuit arrangement for multistage impulse generator

The one-stage equivalent circuit of an impulse voltage circuit with a capacitive load (like power cables and instrument transformers) is drawn in Fig. 3 and that for a power transformer as a load is drawn in Fig. 4. The inductance L_f represents the impulse circuit inductance that is responsible for the overshoot of LI impulses which must be limited to below 5%. This inductance is mainly determined by the geometrical dimensions of the impulse circuit. Similarly L_t is the inductance offered by the tail resistance part of the impulse circuit. These inductances are incorporated in the equivalent circuit to give the VIL a more practical shape.
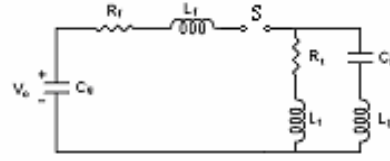

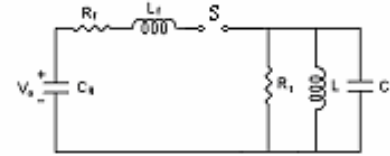Fig. 3. Equivalent circuit for impulse voltage testing of a capacitive load

Fig. 4. Equivalent circuit for impulse voltage testing of power transformer

V_o - Charging voltage, C_g - Generator or Charging capacitance, C_L - Load capacitance, R_f - Front resistance, R_t - Tail resistance, L_f - Front inductance, L_t - Tail inductance, L_L - Load series inductance, L - Load inductance, S - Switch.

For impulse current generation, first the capacitor C_g is charged to a voltage V_o and then the spark gap is triggered. The current impulse is initiated in the circuit whose waveshapes can be adjusted by adjusting the values of R_s and L_s. Fig. 5 shows the equivalent circuit for impulse current generation.
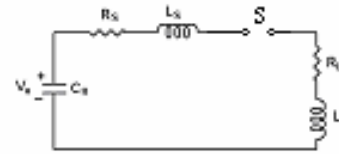

Fig. 5. Equivalent circuit of a basic impulse current testing circuit

3 Mathematical Analysis and Algorithm Development

For the development of the Virtual Impulse Laboratory, a detailed mathematical analysis of the involved impulse voltage and current circuits under the testing conditions has been done to arrive at the algorithms implemented in this web based software module. Solutions for the circuits are obtained using differential equations approach and then corresponding algorithms were developed and implemented in Java to enable web based access.

3.1 Parametric Analysis of Impulse Voltage Generation

To understand the variation in the waveshape and waveform parameters with the variation in circuit parameters, the output voltage is obtained as a function of time for the provided circuit parameters. Two such

circuits for impulse voltage generation are considered here, one in which the load under testing is mainly capacitive like power cables (Fig. 3) and the other in which the load is capacitive with significant inductance in parallel like power transformers (Fig. 4). For each of the circuits, differential equations and appropriate boundary conditions are formulated. The equations obtained are two second order coupled differential equations which are then solved using Finite Differences method [4]. The voltage across the load is obtained as a function of time which can be plotted and the waveform parameters peak value, front time and tail time can be obtained.

3.2 Parametric Analysis of Impulse Current Generation

Similarly, to understand the variation in the waveshape and waveform parameters of an impulse current wave, the output current is obtained as a function of time for the provided circuit parameters. The circuit considered for impulse current generation is shown in Fig. 5 in which the load under testing conditions offers small resistance like surge arresters. The circuit in this case is relatively simpler. It is basically a series R-L-C circuit. The differential equation and appropriate boundary conditions are formulated which can be solved easily. The current through the load is obtained as a function of time which can be plotted and the waveform parameters peak value, front time and tail time can be obtained.

3.3 Analyzer for Pre-selection of Circuit elements of an Impulse Voltage Testing circuit

Power apparatus like transformers, power cables etc. are required to undergo several impulse tests before going into operation. Standard LI and SI impulses for tests have to meet a voltage-time-curve with certain tolerances in accordance with certain specified standards (like IEC 60060-1 [7], IS 2071 [8] etc.). The problem is that the waveshape depends on the test object also which is changing from case to case, so the testing circuit elements have to be changed to obtain the desired waveform across the load. This 'Analyzer' takes as input, the desired waveform specified by front time, tail time and peak value and the load. It then gives as output the value of the testing circuit elements to produce the desired waveform.

For impulse voltage testing circuit (Fig. 3), V_p, T_f and T_t mainly depend on C_g & C_L, R_f and R_t. The approximate formulae for front time and tail time [1] valid under the testing conditions used are:

$$T_f = 3.\frac{C_g C_L}{C_g + C_L}.\frac{R_f R_t}{R_f + R_t} \quad \text{and}$$

$$T_t = 0.7.(C_g + C_L).(R_f + R_t)$$

Ratio of T_f and T_t i.e. T_f/T_t puts upper and lower limits on C_g/C_L.

$$\left(\frac{C_g}{C_L}\right)_{min} = \frac{(1.07\frac{T_t}{T_f}-2)-\sqrt{(1.07\frac{T_t}{T_f}-2)^2-4}}{2} \quad \text{and}$$

$$\left(\frac{C_g}{C_L}\right)_{max} = \frac{(1.07\frac{T_L}{T_f}-2)+\sqrt{(1.07\frac{T_L}{T_f}-2)^2-4}}{2}$$

For example, for a 1.2/50 us impulse voltage wave (C_g/C_L) lies between 0.979 and 42.62. Similarly for 250/2500 us wave, (C_g/C_L) lies between 0.1165 and 8.58.
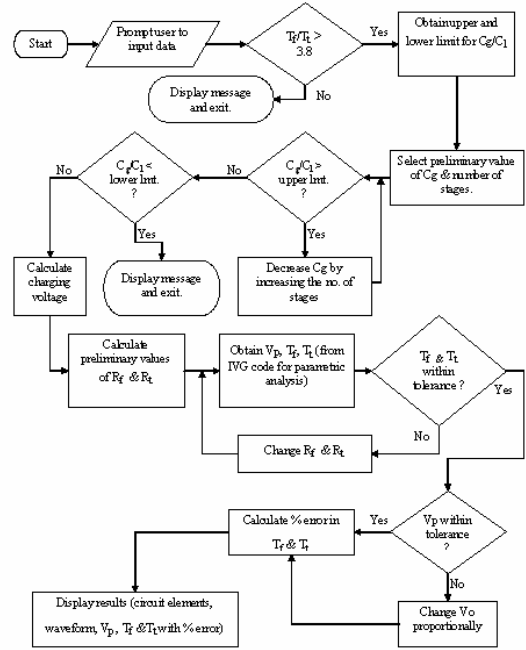

Fig. 6. Algorithm of analyzer for pre-selection of circuit elements of an impulse voltage testing circuit for a capacitive load

The algorithm of analyzer for pre-selection of circuit elements for an impulse voltage testing circuit for a capacitive load is depicted in the flowchart shown in Fig. 6. The user is prompted to input load capacitance (C_L) and waveform parameters $(T_f, T_t$ and $V_p)$. From C_L and T_f/T_t provided by the user, limits on C_g are obtained. As the capacitance units are charged in parallel and discharged in series, the equivalent capacitance of all the charging units decrease as the required peak voltage increases. So depending on the value of peak voltage required and using the limits obtained above, generator capacitance (C_g) can be selected. Now the values of R_f and R_t are obtained using this value of C_g and other parameters already specified (i.e. T_f/T_t and C_L) from approximate formulae used.

Now the values of circuit elements obtained from this approximate analysis are fed to the program made for parametric analysis of impulse voltage generator. The results obtained of our interest are T_f, T_t and V_p. Now T_f/T_t obtained and T_f/T_t desired are compared. If the deviations in obtained and desired values are not within the standard tolerances specified, then appropriate proportional changes in the values of R_S and

R_L are made and new values are again fed to the program. If within the specified tolerances, then V_p is compared and the value of charging voltage is changed proportionally (V_p is directly proportional to charging voltage applied) if so allowed by the limit to which the generator capacitance set (C_g) is charged. Otherwise, the value of Cg is changed (decreased) so that it can be charged to the voltage required. And again the whole procedure is repeated till the required waveform parameters are obtained within the specified tolerances. Some times it might happen that the no solution is reached. But for almost all practical test requirements, the solution is obtained. Similar treatment for the impulse voltage testing circuit for a capacitive and inductive load (Fig. 4) is done and the solution is obtained.

3.4 Analyzer for Pre-selection of Circuit elements of an Impulse Current Testing circuit

The algorithm of analyzer for pre-selection of circuit elements for an impulse current testing circuit is depicted in the flowchart shown in Fig. 7. For impulse current testing, to obtain the values of desired testing circuit elements, the procedure used is first to select a value of the C_g (which is not necessarily the final value to be used in the testing circuit). Now the approximate formulae for front time and tail time for the impulse circuit from which the values of R_S and L_S can be obtained are used. The approximate formulae used are (for underdamped case which is usually the case) [1]:

$$T_f = \frac{1}{\alpha} \sin^{-1} \frac{\alpha}{\alpha}$$

$$T_t = \frac{\pi}{\omega}$$

where

$$\alpha = \frac{R}{2L}, \quad \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

and $R = R_S + R_L$, $L = L_S + L_L$

Now the values of R_S and L_S are obtained using the selected value of C_g and desired front time and tail time using above formulae. The values of circuit elements so obtained from this approximate analysis are sent to the program made for parametric analysis of impulse current generator. The results obtained of our interest are T_f, T_t and I_p. Now T_f/T_t obtained and T_f/T_t desired are compared. If the deviations in obtained and desired values are not within the standard tolerances specified, then appropriate proportional changes in the values of R_S and L_S are made and new values are again sent to the program.

If within the specified tolerances, then I_p is compared and the value of charging voltage is changed proportionally (I_p is directly proportional to charging voltage applied) if so allowed by the limit to which the generator capacitance (C_g) is charged. Otherwise, the value of C_g is changed (decreased) so that it can be charged to the voltage required. And again the whole

procedure is repeated till the required waveform parameters are obtained within the specified tolerances. Some times it might happen that the no solution is reached. But for almost all practical test requirements, the solution is obtained.
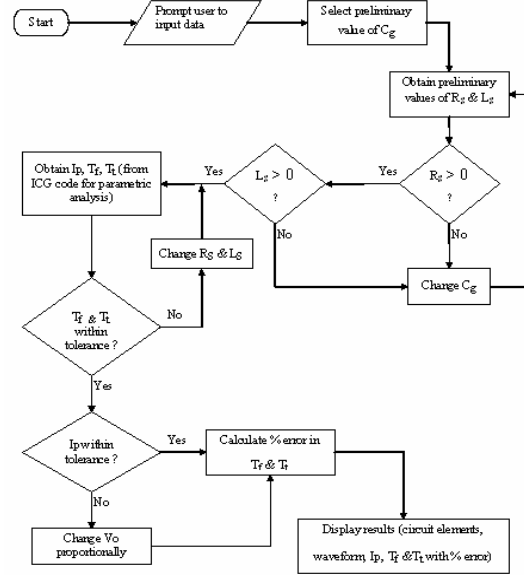

Fig. 7. Algorithm of analyzer for pre-selection of circuit elements of an impulse current testing circuit

4 Software Implementation

Based on the mathematical analysis, algorithms for the implementation of the various facilities of the Virtual Impulse Laboratory were developed. Corresponding codes were written in Java and then given web-based accessibility. The web-based virtual impulse laboratory interacts with the user through a computer interface. The flowchart in Fig. 8 depicts the overall working of this virtual laboratory. The input is fed by the user using the web based interface on the browser of the user's system. These values sent by the client machine are then received by the server. The server processes the input data using the software which runs using programs in Java and PHP. If need arises to access the available database developed using MSSQL, the database is accessed. The output data is then sent to the client machine and is displayed in Java applet on the user's browser.

The C-programs developed for the implementation of the algorithms to obtain the results work well but are compiler dependent. Java programs on the other hand are run (or interpreted) by another program called the Java Virtual Machine (JVM). Rather than running directly on the native operating system, the program is interpreted by the JVM for the native operating system. This means that any computer system with the JVM installed can run Java programs regardless of the computer system on which the applications were

originally developed. Java applets have been used for this purpose in VIL. An applet is a program written in the Java programming language that can be included in an HTML or PHP page, much in the same way an image is included. When a Java technology-enabled browser is used to view a page that contains an applet, the applet's code is transferred to user's system and executed by the browser's Java Virtual Machine (JVM).
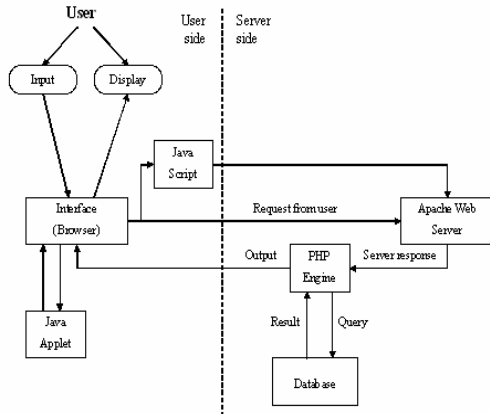

Fig. 8. Overall working of the Virtual Impulse Laboratory

At the heart of any web interaction is the web server. The web server is a program running on the server that listens to the incoming requests and services those requests as they come in. Depending on the type of request, the web server might look for a web page, or it might execute a program on the server. In VIL, the web server is created using Apache/2.0.52 (Win32) PHP/5.0.3. The input fed by the user in interpreted by the browser and request is then made to the server. Server sends the appropriate HTML or PHP code to the user's browser which if required loads the requested applet. The applet processes the input values and displays the results on the user's browser.

For the convenience of the user, a database has been provided enabling him or her to select a power apparatus (standard power cables [5], power transformers and instrument transformers [3] have been included) with standard specifications as a load for impulse testing. This database provides the value of the load corresponding to chosen specifications. For example, it gives the values of the capacitance and the inductance offered by the transformer of chosen rating under the testing conditions. The database also provides the waveform parameters (T_f, T_l and V_p) corresponding to standard impulse test [9] for the chosen power apparatus.

5 Functioning of the Software

The Virtual Impulse Laboratory starts with the home page with two separate links for impulse voltage generation and impulse current generation. Each of these links takes the user to web pages that give him

choice of choosing between parametric analysis of corresponding impulse generator and analyzer for arriving at corresponding impulse testing circuits for impulse testing of a power apparatus. After selection of the proper link, the user is prompted to enter the input values. After processing the input values fed by the user, the output is displayed in java applet which gives the waveform, its parameters and corresponding circuit with circuit constants. For smooth navigation through the Virtual Impulse Laboratory, all web pages have been provided with appropriate links at the bottom.

5.1 Parametric Analysis of Impulse Voltage/Current Generation

For the parametric analysis of impulse voltage generation for a power apparatus, the user is prompted to enter the values of all the circuit elements, charging voltage and the time range in which in response is to be studied. A snapshot of the input screen for the parametric analysis of impulse voltage generation of a capacitive load is shown Fig. 9.
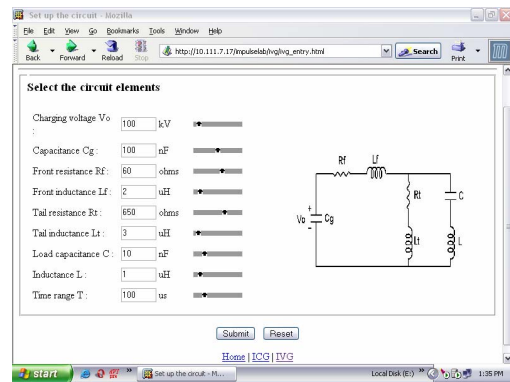

Fig. 9. Input screen for parametric analysis of impulse voltage generation

After the 'submit' button is clicked, a request is sent by the browser to the web server which then loads the appropriate java applet on the user's machine. The processing of the input values is done by the applet and then results are displayed on the user's browser. The snapshot of the output screen corresponding to the input (Fig. 9) is shown in Fig. 10. Similar links for parametric
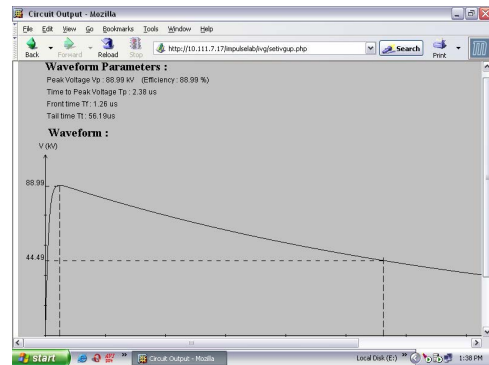

Fig. 10. Output screen corresponding to the input screen shown in Fig. 9

analysis for impulse voltage generation with transformer as a load and the impulse current generation are provided.

5.2 Analyzer for Pre-selection of Circuit elements of an Impulse Voltage/Current Testing circuit

For pre-selection of circuit elements for impulse testing of a power apparatus, user is required to first select the type of load. The user can either provide the load on his own (for example, by specifying the capacitance in case of power cables) or he can select from the database available for the standard power apparatuses. Once the type and ratings of the load are selected, the database provided the capacitance (in case of a power cable) for further processing. After the selection of the load, the user has to input the waveform parameters of the desired impulse wave. Here also the user is provided with options to choose between providing the waveform parameters directly or to let the database select the appropriate waveform parameters which it selects depending upon the load chosen in accordance with Indian standards [8], [9]. A snapshot of the screen showing selected load and waveform parameters for impulse voltage testing of a power transformer is shown in Fig. 11.
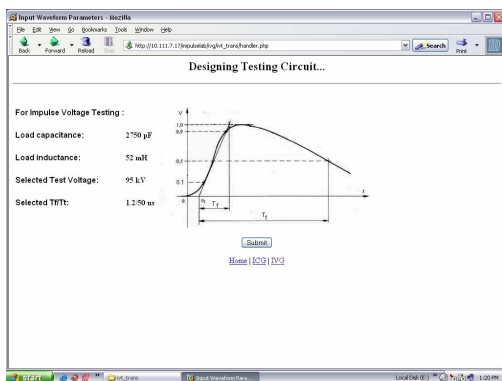

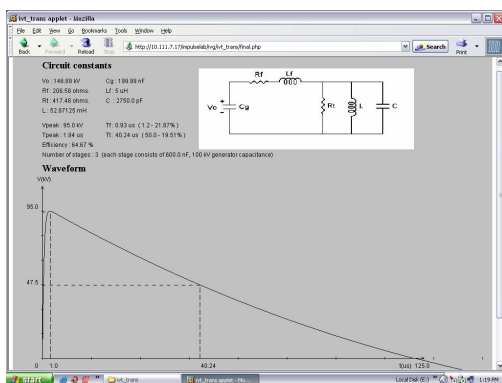Fig. 11. Input screen for pre-selection of testing circuit for impulse testing of a transformer

Fig. 12. Output screen corresponding to the input screen shown in Fig. 11

Snapshot of the corresponding output screen is shown in Fig. 12 which gives the testing circuit and the corresponding waveform. The waveform parameters obtained are within the tolerances specified by Indian standards. Similarly circuit parameters of the testing circuit for impulse voltage testing of capacitive load and for impulse current testing can be obtained.

6   Conclusion

Web based Virtual Impulse Laboratory has been successfully developed for simulating impulse voltage and current generation. It can act as a good tool for teaching and enable a student to understand the influence of circuit parameters on the waveshape. Also it can serve as a guide for the testing engineer to arrive at the values of the generator parameters for impulse testing of various power apparatuses.

The Virtual Impulse Laboratory demonstrates the introduction of the newest information technology in a traditional field like high-voltage engineering. Based on the introduced solution, other special much more complicated problems of impulse testing can be made accessible.

References

[1] M. S. Naidu and V Kamaraju, *High Voltage Engineering*, 2nd ed. New Delhi: Tata McGraw Hill, 1995, p.129-147.

[2] W. G. Hawley, *Impulse Voltage Testing*, 1st ed. Chapman & Company, 1959.

[3] Allen Greenwood, *Electrical Transients in Power Systems*, 1st ed. John Wiley & Sons, 1971.

[4] B. S. Grewal, *Higher Engineering Mathematics*. New Delhi: Khanna Publishers, 1976.

[5] G. F. Moore, *Electrical Cable Handbook: BICC Cables*, 3rd ed. London: Blackwell Science, 1997.

[6] N Liester and W Schufft, "*Virtual ASP based Impulse Generator*", presented at the 12th Int. Symposium on High Voltage Engineering, Netherlands, 2003.

[7] IEC 60060-1, High Voltage Test Techniques. Part 1: General definitions and test requirements.

[8] IS 2071, Indian Standard specifications for *High Voltage Test Techniques*, Bureau of Indian Standards, New Delhi, November 1996.

[9] IS 2026, Indian Standard specifications for *Power Transformers*, Bureau of Indian Standards, New Delhi, January 1997.

[10] B. Hemalatha & Dipak Kumar Pal , "*A JSP based Impulse voltage Generator*", Proceedings 13th National Power Systems Conference (NPSC-2004), Chennai, India pp 862-865 (2004).