CHARACTERIZATION OF THE INSULATION STRENGTH OF ELECTRICAL EQUIPMENT THROUGH IMPULSE GENERATOR

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***ABSTRACT*─** *In this paper we have investigated the insulation strength of power equipment using a single-stage impulse generator and developing a simulation model of the impulse generator including the effects of the parameters which influence its behavior. The high frequency equivalent simulation model of the impulse generator is developed in MATLAB including the effect of stray capacitance and the wave-shaping inductance. The impulse generator is then modeled to determine its transfer function so that the actual output of the impulse generator can be compared with the simulations and the analytical outputs to verify the accuracy of the two models (simulated and mathematical). A transformer is used as the test power apparatus. The high-frequency model of the transformer is utilized because of high frequency components present in the impulse voltage. The insulation failures at various locations of the winding are simulated and the resultant curves are obtained for different times of insulation breakdown on the impulse wave.*

Keywords: Impulse generator, Wave shaping, Insulation failure,

INTRODUCTION

The electrical power systems have grown enormously in the last few decades. The continuously increasing power demands are translated directly to the transmission networks capacities which result in increased ratings of the power apparatus. Power is transmitted at higher voltages for economic and (better) efficiency reasons. The impact of this ever-increasing power demand is that huge amount of power has to be transmitted from the generating stations to the load centers via transmission lines [1,2]. An attempt to reduce the current results in an increase in the voltage ratings of the power equipment to be used in the transmisson networks [3], [4]. With an increase in the voltage ratings, the insulation requirements of the power equipment also increase [5]. Proper insulation plays a vital role not only in improving the efficiency of the power apparatus but it also enhances the life span of the power apparatus. Thus the insulation of the power apparatus is needed to withstand the worst possible conditions which can occur under fault or transient conditions. Therefore, the insulation of equipment must be tested for all the possible practical situations before it is installed practically in a system. The equipment used for testing the insulation of the power apparatus must be capable of producing the output very similar to the actual working conditions [6].

The increased voltage ratings of the power equipment require that their insulation should be adequate enough to withstand not only the normal working voltages but also the transient voltages which occur on the power systems due to lightning or switching mechanisms. This necessitates the requirement of having the insulation of the power apparatus tested under various conditions before it is actually installed in the network. The testing equipment should be capable of producing the same voltage levels and the same wave shapes which the equipment is deemed to come across in a practical situation. The gigantic increase in the power demand has enhanced the vitality of the insulation coordination and protection of the power system by manifolds. Therefore, a lot more attention is needed to be paid to the insulation of the power equipment during the design and testing phases. Thus the insulation must be tested under all possible practical conditions such as normal, fault and transient conditions as the failure of insulation may ultimately affect the stability of the whole power system [7].

The standard equipment which is usually used for the testing of the insulation of power apparatus is the high-voltage impulse generator which has the ability of generating the same wave shapes as are required for standardized testing. The insulation of the power apparatus can be tested under transient conditions with the help of an impulse generator [8]. An impulse is a unidirectional voltage wave of very short time interval having very fast rise and fall times. These rapid rise and fall times develop strong electrostatic forces on the insulation strength of the power apparatus causing partial or complete failure of the insulation if the insulation was not properly designed and tested [9].

In this paper, we have simulated a single-stage high-voltage impulse generator developed in MATLAB. After the formation of the simulation model, its output is compared with the impulse voltage actually produced by the impulse generator. Then the output of the simulation model is calibrated by taking into account the effect of stray capacitance and other parameters. The model of a transformer as an electrical apparatus is tested against impulse voltage. Since an impulse contains very high frequency components, a simple transformer model cannot be used for accurate results and it becomes imperative to modify the simple transformer model so that it takes into account the high-frequency components present in the impulse voltage wave [10], [11]. Therefore, a high-frequency model of a transformer is used so that the results become as practical as possible.

For the purpose of insulation investigation, different insulation failure scenarios are simulated on the transformer model on the application of an impulse wave and results are obtained which clearly show the impact of insulation failure on the output waveform.

DESIGN PROBLEM

Studies of the power transmission-systems disturbances have shown that lightning and switching phenomena are succeeded by impulse waves of very abrupt rise time. An impulse voltage wave can be represented by the difference of two negative exponential functions as given by equation

$$v_o(t) = K * V_c\left(e^{-\alpha*t} - e^{-\beta*t}\right), \qquad (1)$$

where $v_o(t)$ is the output voltage, V_c is total voltage across the charging capacitors, while K, α and β are constants which depend upon the circuit parameters [12].

The standard equipment used to test the insulation strength of the power apparatus before installing them in the power system is a high-voltage impulse generator. A high-voltage impulse generator is capable of producing the same wave shape with the same wave-front and wave-tail times as required by the standards [13], [14], [15], [16]. An impulse generator can simulate the same practical transient situations as the power apparatus is deemed to come across when it is installed practically in a power system. An impulse generator is employed to verify that the power apparatus will function properly and can withstand all the possible transient conditions in its life span.

Simulation modeling

A single-stage impulse generator is a small impulse generator having low energy [8]. The peak value of the output voltage of this type of generator is also not very high as compared with that of a multi-stage impulse generator. A typical circuit of a single-stage impulse generator is shown in Figure 1.

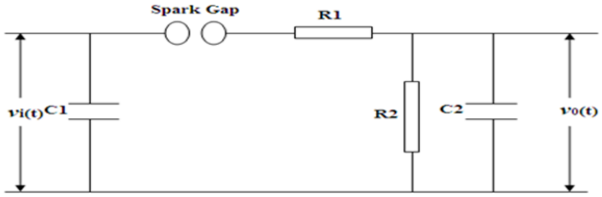

Figure 1: Circuit diagram of a single-stage impulse generator

Where Capacitor C_1 is the charging capacitor which is charged with the help of a DC voltage source. Resistor R_1 is the wave-front control resistor while R_2 is the wave-tail control resistor. Capacitor C_2 is the capacitance of the load. A single-stage impulse generator can be used to generate a maximum of 200 kV [7]. The values of the these components for the impulse generator present in the Laboratory are given in Table 1. There are certain other parameters as well which affect the output impulse voltage other than the ones which have been described above. These include the inductance of impulse generator, if available, the stray capacitance, resistance of the spark gap, inductance of the leads and load.

After incorporating all the parameters which may affect the output of the impulse generator, the next step is to develop the simulation model of the impulse generator in MATLAB. To do so, *SimPowerSystems* Library within MATLAB Simulink has been utilized. The simulation model of the impulse generator developed in MATLAB is shown in Figure 2.

Table 1. Component Specifications

Serial No.	Component Name	Value
1.	Charging capacitance, C_1	$0.125\text{x}10^{-6}$ F
2.	Wave-front resistance, R_1	40 Ω
3.	Wave-tail resistance, R_2	557 Ω

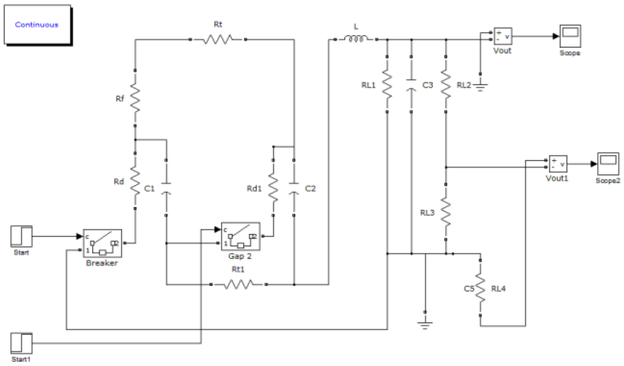

Figure 2: Simulation model of the impulse generator

The spark gaps have been modelled with the help of breakers whose operation has been controlled with the step-response block. Resistance R_d and R_{d1} form the wave-front control resistances while the resistance R_{L1} is the wave-tail controller resistance. R_{L2}, R_{L3} and R_{L4} are the resistance used as potential dividers in order to measure the output voltage in a safe limit. C_1 and C_2 are the charging capacitances while C_3 is the stray capacitance. L is the inductance of the impulse generator which plays its part in shaping the impulse wave. When the step response in applied to the breakers, the charging capacitances C_1 and C_2 come in series with the resistances R_d and R_{d1} and an impulse is imposed on the output through inductance L and resistance R_{L1}. The *Scope* displays the actual simulated impulse while *Scope2* displays the simulated impulse after potential divider circuit.

To verify the accuracy and reliability of the output of the simulated model, it is compared with the actual output of the impulse generator obtained practically. The data from the impulse generator can be recorded with the help of a Digital Storage Oscilloscope (DSO) which is connected with the output of the impulse generator. The two impulse waveforms plotted on the same graph in MATLAB are shown in Figure 3. The blue curve with some ups and downs shows the output of the actual impulse generator. This graph is plotted with the help of a CSV file. The red curve shows the output of the simulation model of the impulse generator. It can clearly be seen that the two graphs are overlapping for the most of the time which establishes the reliability of the simulation model and it means that this model of the impulse generator can be used for further simulation studies.

The single-stage impulse generator can be modeled mathematically as well. First of all the circuit diagram of the impulse generator is converted into Laplace domain. Then KCL is applied at various nodes of the circuit to find out the equations for node voltages. After that the transfer function of the impulse generator is found out by taking the ratio of the output voltage to the input voltage.

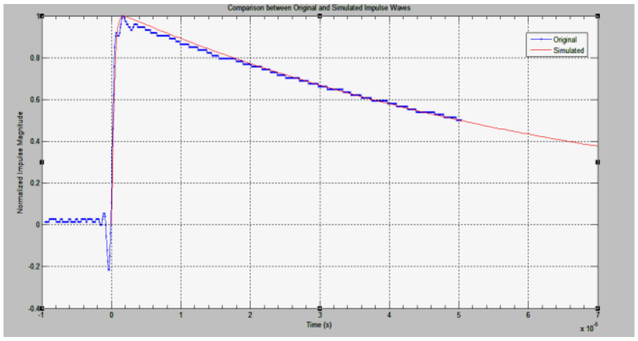

Figure 3: Graph showing the comparison between actual impulse and the simulated impulse

The transfer function in Laplace domain can be converted back into the time domain by taking the Inverse Laplace Transform of the transfer function. The graph of the time domain transfer function will give us the output impulse voltage of the generator versus time. This graph can be compared with the output graph of the simulated model to establish the validity of the mathematical model as well.

In order to find out the transfer function of the impulse generator, the circuit diagram of the impulse generator is converted into the Laplace domain. Figure 4 shows the impulse generator circuit transformed into Laplace domain.

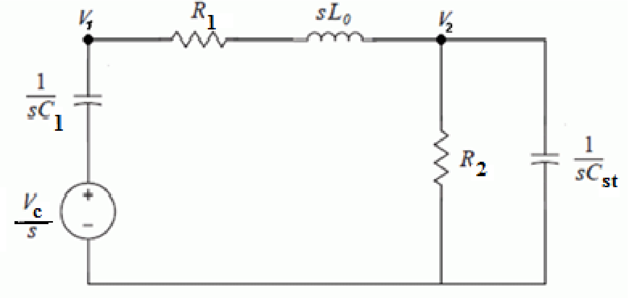

Figure 4: Circuit diagram of impulse generator transformed into Laplace domain.

$$\frac{V_2}{V_C} = \frac{1}{C_{st}L_o} \cdot \left(\frac{1}{s^3 + \left(\frac{R_1}{L_o} + \frac{1}{C_{st}R_2}\right)s^2 + \left(\frac{1}{C_{st}L_o} + \frac{R_1}{C_{st}R_2L_o} + \frac{1}{C_1L_o}\right)s + \frac{1}{C_{st}C_1R_2L_o}} \right), \quad (2)$$

V_2/V_C is the transfer function of the impulse generator in Laplace domain. It can clearly be seen that this is a very complicated relationship which is composed of various parameters of the impulse generator. Table 2 shows the values of all the parameters of the impulse generator present in equation 2

$$\frac{V_2}{V_C} = \frac{2.8153 * 10^{13}}{s^3 + 11.401 * 10^6 s^2 + 3.021 * 10^{13} s + 4.044 * 10^{17}}, \quad (3)$$

Which in time domain is

$$\frac{V_2}{V_C} = 1.26899e^{-7.23074*10^6 t} - 2.21044e^{-4.1568*10^6 t} + 0.941454e^{-13454.5t}, (4)$$

From equation 4, the output impulse can be easily calculated by multiplying the transfer function with the value of the voltage on the charging capacitors. Now the output of the mathematical model can be compared with the output of the simulated model on a single graph to show the validity of the mathematical model of the transfer function. The graph showing the comparison between the two outputs is shown in Figure 5. For simplicity, both the voltage magnitudes have been normalized to unity.

Table 2: Values of the parameters to be used in equation

Serial No.	**Component Name**	**Values**
1.	Charging capacitance, C_1	0.125x10^{-6} F
2.	Resistance, R1	40 Ω
3.	Resistance, R2	557 Ω
4.	Inductance, Lo	222x10^{-6} H

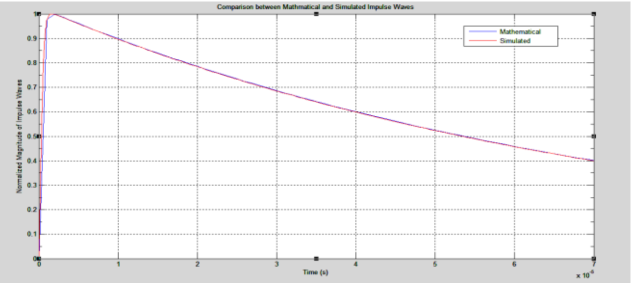

Figure 5: Comparison of outputs of mathematical and simulated models of impulse generator

The graph clearly shows almost a complete overlap of the two impulse voltages which establishes the validity of the mathematical model of the impulse generator.

INSULATION INVESTIGATION AND RESULTS

We have used a transformer as a test power apparatus for the investigation of its insulation. The output of impulse generator is applied on the transformer and insulation failure situation is simulated for failure at various positions within the winding. But the problem is that due to the presence of high-frequency components in an impulse voltage, the general equivalent model of a transformer cannot be used because at high frequencies, the internal capacitances of the windings become significant and can no longer be ignored [11]. Therefore, there is a need to modify the equivalent model of a transformer in order to more accurately simulate the actual practical conditions using MATLAB.

Results are obtained by simulating various insulation fault conditions in the winding of the transformer. In the end, the outputs under various fault conditions are analyzed by plotting and comparing the frequency responses of all the simulated fault conditions. Standards are available for specifying proper insulation levels of all the power apparatus. Therefore, the insulation levels of the power apparatus must be designed according to the standards [17]. Once the insulation is designed, it should be tested according to the standards. One of the standards is to test the insulation of the power apparatus against the lightning impulses with the help of an impulse generator. The test object is connected at the output of the impulse generator and impulses are applied on it according to the standards. The values of various parameters of transformer used in the simulation model of the test transformer have been tabulated in Table 3 [18].

The simulated parametric model as defined in Table 3 is attached with the simulation model of impulse generator of Figure 2 in order to simulate the failure of the insulation. An impulse is applied on the high-frequency model of the transformer with the help of the impulse generator and the output voltage is recorded with the help of *Scope1* attached at the output of the circuit. The impulse voltage thus obtained is shown in Figure 6. A comparison of the output voltage with and without the transformer has been depicted in Figure 7.

Table 3: Parametric Values of the Test Transformer

Sr.#	Parameter	Value
1.	No. of phases	1
2.	kVA rating	5
3.	Primary voltage (V)	110
4.	Secondary voltage (V)	95
5.	Resistance of primary winding (Ω)	325
6.	Resistance of secondary winding referred to primary side (Ω)	275
7.	Inductance of primary winding (mH)	130
8.	Inductance of secondary winding referred to primary side (mH)	110
9.	Resistance of magnetic branch R_m (Ω)	90
10.	Inductance of magnetic branch L_m (mH)	5
11.	Primary winding stray capacitance C_p (nF)	0.26
12.	Secondary winding stray capacitance C_s (nF)	0.24
13.	Mutual stray capacitance between primary & secondary windings C_{ps} (nF)	0.3

A good degree of resemblance can be observed in the two waveforms of Figure 7. However, the impulse with the transformer decays slightly earlier than the impulse without the transformer and the former shows an abrupt jump at the peak as well. These two differences can readily be explained: the slightly earlier decay is because of the fact that a transformer has been connected as a load in parallel with the output resistance of the impulse generator which reduces the output impedance and, hence, decay time has been reduced. The reason for abrupt jump at the output is due to the stray capacitance of the transformer.

The failure of the insulation is simulated by reduction in the impedance of the transformer. If the insulation of the winding is weak at some point, it may be shorted with the core of the transformer which results in a direct short circuit between the winding and the core. The output voltage will depend upon the impedance of the healthy portion of the winding. For example, if insulation failure occurs at 10% of the winding from the top, the remaining 90% of the winding will be shorted and the output voltage will depend upon impedance of the healthy part which is just 10% of the total winding impedance. We have simulated the insulation failure at 1%, 10% and 50% of the winding from the top and results are obtained with the help of MATLAB.

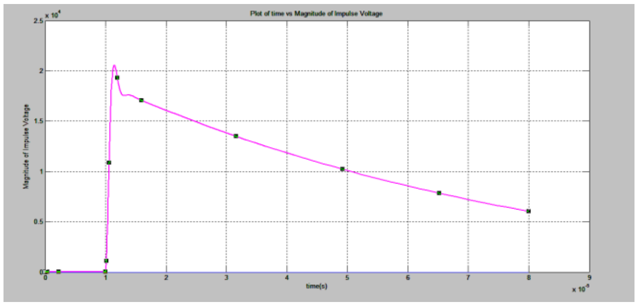

Figure 6: Impulse voltage at the output of the transformer.

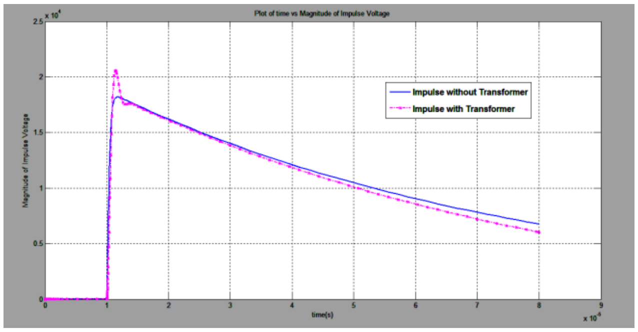

Figure 7: Comparison of output voltages with and without transformer connected to the impulse generator.

The timing of the insulation failure is also important on the application of an impulse. When an impulse voltage is applied on the insulation, huge amount of stresses are produced in the insulation. The insulation may collapse partially or completely as a consequence of these stresses. This collapse may take place at any point on the impulse wave. Therefore, the insulation failure has been studied at various points on the impulse wave. Strength of the insulation is investigated by simulating failure of the insulation at various points on the winding length at different instants of time and the output impulse voltages are plotted. For the analysis of these results, frequency responses of all the results are also plotted in figure 8 ((a) – (f)), where Blue line shows actual impulse without transformer, Black, Red and Green lines correspond to fault at 1 % of the winding, 10 % of the winding and 50 % of the winding respectively. These frequency response curves show that the more the output voltages are closer to the actual impulse voltage, the less dispersed will be the frequency response of the faulted cases from the frequency response of the actual impulse and vice versa. Similarly, the quickly the insulation collapses, the frequency response will have more high frequency components and vice versa. Thus the frequency response of the output impulse voltage can be used to predict the presence of insulation failure.

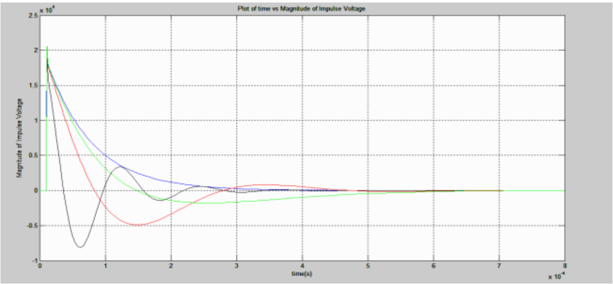

Figure 8(a): Output voltages for faults simulated at t = 0.

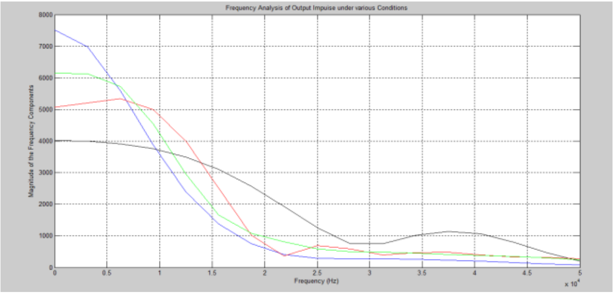

Figure 8(b): Frequency response for faults simulated at t=0.

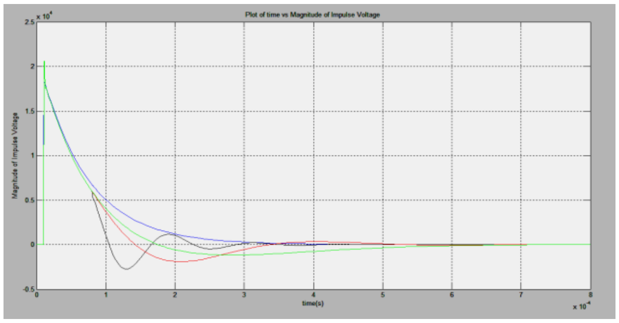

Figure 8(c): Output voltages for faults simulated at t = 0.8x10-4.

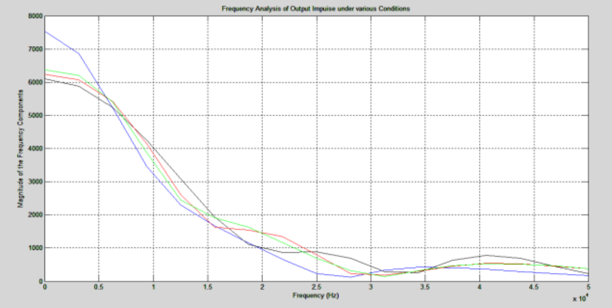

Figure 8(d): Frequency response for faults simulated at t = 0.8x10-4.

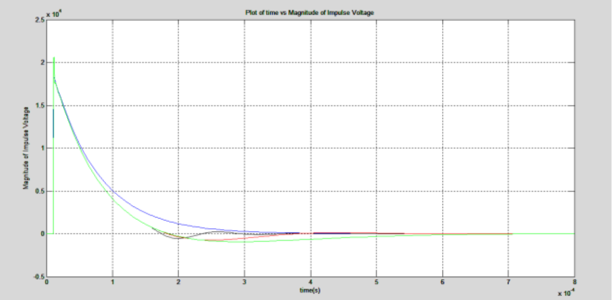

Figure 8(e): Output voltages for faults simulated at t = 1.6x10-4.

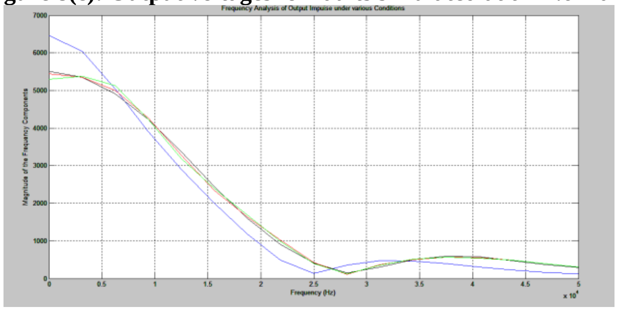

Figure 8(f): Frequency response for faults simulated at t = 1.6x10-4.

CONCLUSION

In this paper we have investigated the insulation of power equipment using a single-stage impulse generator and developing a simulation model of the impulse generator including the effects of the parameters which influence its behavior. We have come up with the following results. (a) Insulation strength of the all the power apparatus must be tested before installing it in a practical power system. (b) To analyze the performance of a transformer on impulse voltages, the simple equivalent model of the transformer cannot be used due to the pronounced effect of the stray capacitance at these impulse voltages. Therefore, a high-frequency model of a transformer is needed to be used in the analysis. (c) If the insulation of the winding is weak, the impulse will decay to zero rather quickly and the decay time will depend on the percentage of the insulation which is shorted. (d) The more the output voltages are closer to the actual impulse voltage, the less dispersed will be frequency response of the faulted cases from the frequency response of the actual impulse and vice versa. (e) The quickly the insulation collapses, the frequency response will have more high frequency components than the low frequency components and vice versa. (f) The frequency response of the output impulse voltage can be used to predict the presence of insulation failure.

These results have been demonstrated with the help of numerous mathematical expressions, graphs and comparisons.

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