Impulse Testing of Power Cables-Simulation Cum Experimental Approach

Arunjothi. R
Central Power Research Institute
Bangalore, India

Thirumurthy, Meena K P
Central Power Research Institute, India
Bangalore, India

***Abstract*—The capability to withstand the lightning transients is a mandatory requirement for any high voltage equipment, especially power cable system. As a type test, this test is carried out on the cable system of about 20 to 25 metres length of cable mounted with all accessories and at the applicable Basic Impulse Level voltage (BIL) of that system. Generally, the selection of number of stages, rise time resistors, tail resistors etc to get the required Lightning Impulse wave shape within the tolerance limit is achieved by trial and error method. When the test is carried out at higher voltages this process of changing resistors will become a tedious process. Hence, an effort is made to simulate the Impulse Generator in MATLAB Simulink, which will help to decide the number of stages, and proper resistor values according to the sample capacitance and test voltage. The test results from the simulation are compared with the experimental test results of the impulse generator for various power cable systems. The results of the Impulse simulation and experimental work are observed to be within ±5 % variation. Hence the simulation of the circuit of Impulse Generator is helpful to arrive at the resistance values and number of stages to be used for the testing of a particular cable system.**

Keywords*—*Lightning Impulse; Power Cable System;

I. INTRODUCTION

Electrical Insulation Systems are prone to experience overvoltage transients from lightning strikes and they should withstand such a severe sudden overvoltage conditions caused by lightning. High-Voltage Impulse Testing is performed to assess the ability of Electrical Insulation Systems to withstand such high-voltage impulses. High Voltage Impulse testing is part of type test for electrical equipment like transformers, motors, coils, Power cables, switches, circuit breakers, surge protection devices and individual insulation materials. The type test simulates the real stresses of the cable system reasonably and checks the performance and lifetime operation of the cable system.

Unlike other products, Impulse test on Power cable systems are generally carried out at an elevated conductor temperature of 95 to 100 ° C. The sample should withstand ten positive and ten negative impulse shots at elevated conductor temperature. For cable systems, before applying the impulse voltage, the cable is heated by passing suitable current through the cable to raise the conductor temperature to a temperature between 95 to 100 °C. After 2 hours of reaching the stabilized conductor temperature, the sample will be subjected to 10 positive and 10 negative impulse voltage applications.

II. IMPULSE GENERATOR

The rated capacity of the Impulse Generator in the laboratory is 2400 kV and 240 kJ. There are 24 stages in the impulse generator with maximum charging voltage of 100 kV per stage. In each stage, two charging capacitors of rating 4 µF are connected in series. The capacitors in the connected stages are charged in parallel to a voltage V relative to ground. When the bottom sphere gap is triggered by voltage injection, discharging of the stage capacitors happens in series through the resistors, cumulatively raising the voltage to nV, where n is the number of stages and V is the charging voltage per stage. The actual voltage is measured through the 2400 kV RC high voltage divider of 1750 Ratio.

The basic impulse levels (BIL) of different voltage rating of the Power cables are given in Table I. The basic lightning impulse wave shape is defined by 1.2/50 µs. 1.2 micro second refers to the front time of an impulse wave, which is the time taken by the wave to reach to its maximum value starting from zero value. Since it is difficult to identify the start and peak points of the lightning impulse the front time is specified as (1/0.6) times $(t_2 - t_1)$, where t_2 is the time for the wave to reach to its 90% of the peak value and t_1 is the time to reach 30% of the peak value. Since $(t_2 - t_1)$ represents about 60% of the front time, it is multiplied by (1/0.6) to give front time of the lightning impulse [1]. Similarly 50 micro second refers to the tail time, which is the time between peak values to 50 % of peak [2].

TABLE I. BASIC IMPULSE VOLTAGE OF CABLES OF VARIOUS RATINGS

Cable Rated voltage, kV (RMS)	Impulse Test Voltages, kV (Peak)
6.35/11	75 or 95
8.7/15	95 or 112
11/11	95
12/20	125
12.7/22	125 or 144
18/30	170
19/33	170 or 194
26/45	250
38/66	325
66/132	550
127/220	1050

III. IMPULSE TESTING OF POWER CABLE SYSTEMS UNDER NO LOAD

Simulation of Impulse generator is carried out by MATLAB Simulink. The impulse parameters of the same experimental condition were also simulated in MATLAB by incorporating the 350 pF divider. Along with divider internal damping resistance of 360 Ω and external damping resistor of 250 Ω are also connected in the test circuit.

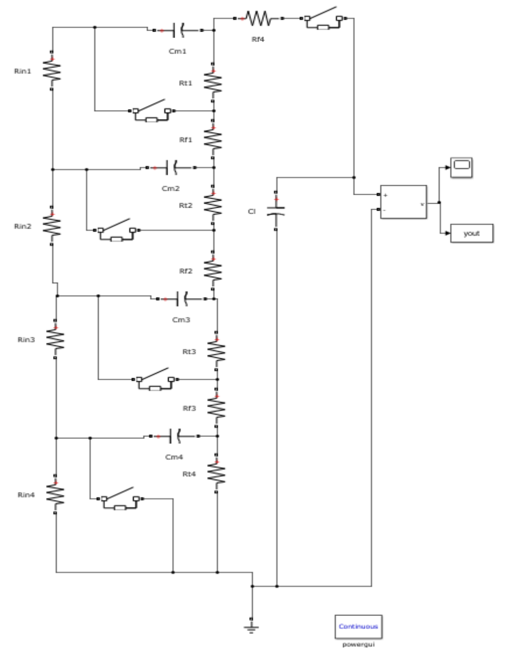


Fig. 1. Four stage Impulse Generator simulation in Simulink

Impulse voltage generator is developed in MATLAB Simulink with standard blocks available in Simulink. The twenty four stage impulse voltage generator is simulated with the software. The sphere gaps of the stages were simulated by the use of switches [3]. And each of the stage capacitors was assigned an initial charge voltage value, which is equal to the actual charging voltage applied per stage during the actual test. The values of front and tail resistors, as well as the stage capacitors, are the same as used in the actual impulse generator. The simulation circuit considered for 24 stages is a expanded version of the four stage simulation shown in Figure 1.

A small program is written in MATLAB which automatically derives the t_1 and t_2 values from the simulated lightning impulse and calculates the front time of the simulated impulse. In this simulation circuit the equivalent capacitance of each stage capacitors is considered in the circuit. The laboratory and simulation results of voltage test are as given in Table II and Table III.

TABLE II. PEAK VOLTAGE OF IMPULSE WAVEFORM BY EXPERIMENTAL AND SIMULATION AT NO LOAD

No of stage of the generator	**Charging Voltage Per stage (kV)**		**Peak Voltage (kV)**		**Efficiency of the Impulse Generator (%)**	
	Simulation	Experiment	Simulation	Experiment	Simulation	Experiment
24	-100	-100	-1829	-2276	76.2	94.4
24	+90	+90	1653	2016	76.5	92.8

TABLE III. FRONT & TAIL TIME OF IMPULSE WAVEFORM BY EXPERIMENTAL AND SIMULATION AT NO LOAD

No of stages of the generator	**Front Time (µS)**		**Tail Time (µS)**	
	Simulation	**Experiment**	**Simulation**	**Experiment**
24	1.15	1.2	49.58	50

From the Table II and III, it is evident that the front time and tail time parameters are exactly matching for both experiment and simulation. The time parameters are same for both positive and negative polarities in the case simulation and as well as experiment. However the peak voltage and efficiency of the generator of both the cases are not matching in no load condition.

In this simulation circuit, each stage consists of one resultant charging capacitor, however in the actual impulse generator two capacitors are connected in series and each stage capacitors are connected through potential resistors (R_{pot}) as shown in Figure 2. Since the simulation model of Figure 1 is not exactly reflecting the actual impulse generator, the simulation circuit was modified to include potential resistors connected between stages through the two series charging capacitors. The modified four stage equivalent simulation circuit is as given below in Figure 2.

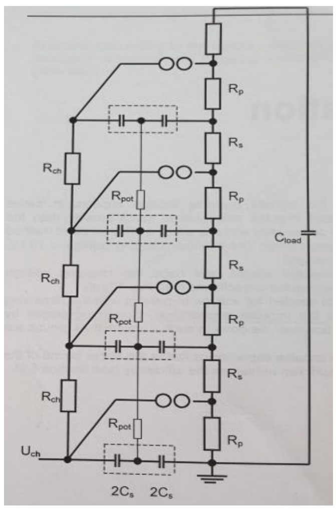


Fig. 2. Modified Four stage equivalent simulation circuit in Simulink

Now the impulse voltage test was conducted using the modified 24 stage simulation circuit to check with the results of experimental work. In this case, each series capacitor of the stage is assigned half of the charging voltage. Table IV shows the peak voltage & efficiency obtained from simulation and experiment work.

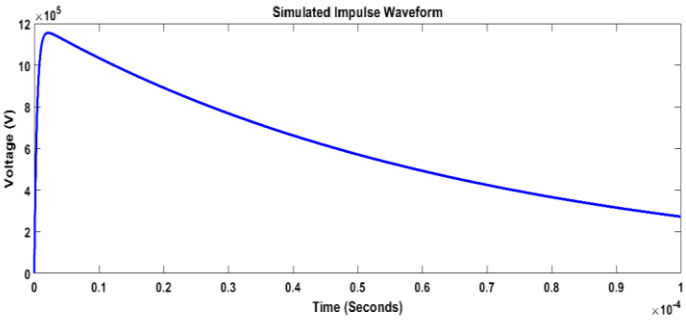
TABLE IV. PEAK VOLTAGE OF IMPULSE WAVEFORM BY EXPERIMENTAL AND MODIFIED SIMULATION AT NO LOAD

No of stages of the generator	**Charging Voltage Per stage (kV)**		**Peak Voltage (kV)**		**Efficiency of the Impulse Generator (%)**	
	Simulation	**Experiment**	**Simulation**	**Experiment**	**Simulation**	**Experiment**
24	-100	-100	-2311	-2276	96.3	94.4
24	+90	+90	2080	2016	96.3	92.8
24	-50	-50	-1155	-1109	96.3	92.4
24	+50	+50	1155	1133	96.3	94.4

Here the numbers of stages used are 24 and the results from both positive and negative polarity results are correlated. Similarly, Table V shows the front and tail time parameters of simulated and experimental work. The time parameters are same for positive and negative polarities. They are also not changing with respect to the charging voltage. Figure 3 shows the Lightning Impulse curve of the simulation.

TABLE V. FRONT & TAIL TIME OF IMPULSE WAVEFORM BY EXPERIMENTAL AND MODIFIED SIMULATION AT NO LOAD

No of stages of the generator	Front Time (µS)		Tail Time (µS)	
	Simulation	Experiment	Simulation	Experiment
24	1.27	1.2	49.23	50



Fig, 3. Simulated Lightning Impulse Waveform

IV. IMPULSE TESTING OF POWER CABLE SYSTEMS UNDER LOAD

The various cables and cable systems of different voltage ratings are subjected for lightning impulse test and the number of stages are being selected as per the impulse voltage levels from 4 to 19.

The details of Cable systems tested, the total capacitance of the cable systems and the number stages used for lightning impulse testing are as given below in Table VI. Figure 4 shows the mounting arrangement of the 220 kV Cable system for lightning impulse test.

The simulation circuit as per figure 2 is built in MATLAB Simulink considering the cable as a capacitive load and the actual measured capacitance of each cable is used in the simulation circuit [4] [5]. In this simulation circuit with test object load, the results observed in both the simulation and experiments are given in the tables VII and VIII.

TABLE VI. PEAK VOLTAGE OF IMPULSE WAVEFORM BY EXPERIMENTAL AND SIMULATION AT LOAD WITH MODIFIED SIMULATION

Sl.No	Particulars of Cable	Capacitance (nF)	No of stages used
1	3C X 400 sq.mm 19/33 kV XLPE insulated Cable with accessories	2.711	4
2	1X 630 Sq.mm, 64/110 kV XLPE insulated Cable with accessories	3.828	10
3	1C X 1200 Sq.mm, XLPE Insulated 127/220 kV Cable with accessories	4.450	19
4	1CX1200 Sq.mm, XLPE Insulated, 127/ 220 kV Cable with accessories	4.213	19
5	1C X 2000 Sq.mm, XLPE Insulated, 127/ 220 kV Cable with accessories	5.163	19
6	1C X 300 Sq.mm, XLPE Insulated, 76/132 kV Cable with accessories	3.029	11

Fig.4. Impulse test set up of a 220 kV XLPE Cable System

The peak voltage, front time and tail time observed with different combinations of stages for cables by simulation and as well as experimental are given in the Tables VII and VIII.

TABLE VII. PEAK VOLTAGE OF IMPULSE WAVEFORM BY EXPERIMENTAL AND SIMULATION WITH LOAD

No of stages of the generator	Charging Voltage Per stage (kV)		Peak Voltage (kV)		Efficiency of the Impulse Generator (%)	
	Simulation	Experiment	Simulation	Experiment	Simulation	Experiment
4	44.5	42.7	169.5	170.6	95.5	99.6
10	58.5	55.5	543	545	92.8	98.2
19	61	58.2	1046	1050	90.3	95.0
19	60.5	57.9	1050	1050	91.3	95.5
19	61.5	58.0	1046	1048	89.5	95.0
11	63	58.8	651	650	93.9	99.5

From Table VII, it is observed that the peak voltage and the efficiency obtained in the simulation is always 3.5 to 5.5 percent lesser than the actual impulse voltage achieved in the laboratory. Table VIII shows the front time and tail time of the impulse waveform obtained through experimental method and simulation.

TABLE VIII. FRONT & TAIL TIME OF IMPULSE WAVEFORM BY EXPERIMENTAL AND SIMULATION WITH LOAD

No of stages of the generator	Front Time (µS)		Tail Time (µS)	
	Simulation	Experiment	Simulation	Experiment
4	1.55	1.58	46.91	45.37
10	2.20	1.91	49.39	48.79
19	2.59	2.42	52.53	51.32
19	2.17	2.26	53.27	51.13
19	2.70	2.57	53.43	51.53
11	1.82	1.94	48.85	48.50

From Table VIII, it is evident that the time parameters of simulation and experimental work are very much comparable. Figure.5 shows the simulated negative polarity lightning impulse of 650 kV peak using 11 stages of simulation. Figure 6 shows the experimental waveform of 1048 kV peak voltage obtained using 19 stages of impulse generator.

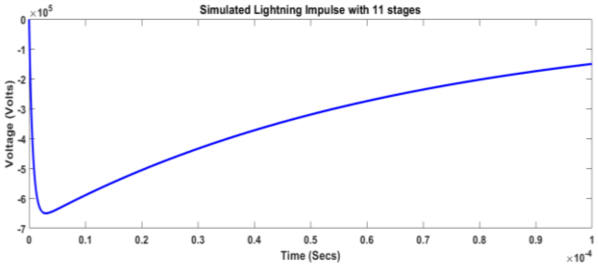


Fig. 5. Simulated Lightning Impulse Waveform of negative polarity

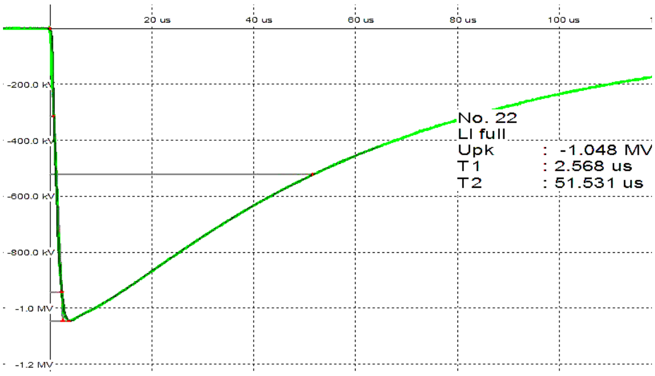


Fig.6. Experimental Lightning Impulse Waveform of negative polarity

CONCLUSION

Both actual Impulse Generator and Simulated Impulse Generator have almost similar output, validating the MATLAB model both in no load condition and with load of test samples of various capacitances. The minor variations may be due to change in capacitance at elevated temperature and the effect of stray capacitances. This simulated model can be used to fix the tail and rise time resistors and number of stages for actual testing. The comparison was done for various cable samples of different capacitances and voltage rating. From the comparable results of experiment and simulation, it can be concluded that if the sample capacitance is known the number of stages and the value of front and tail resistors can be chosen from the simulation for the desired wave shape. By this way, the time and manpower can be utilized optimally to achieve the desired wave shape without subjecting the test sample for trial test.

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