STUDIES ON LIGHTNING CHARACTERISTICS

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ABSTRACT

Power systems components are subjected to lightning and switching over-voltages. These voltages/ currents are momentary and it is required to test the above said power equipment's against such conditions. Marx generator is used to produce standard lightning impulse of 1.2/ 50 µs and switching impulse of 250/ 2500 µs. In the present work designing, fabrication of wave-shaping resistors and load capacitance for a given 200 kV Marx generator were carried out. The duration of the generated lightning impulse waveform is compared with standard duration and the simulation analysis is carried out using PSPICE. Also work has been carried out in designing a 100 pF, 200 kV cylindrical capacitor. To study the importance of insulation in high voltage capacitor, estimation of electric field is carried out using ANSYS software.

Keywords – *Marx generator, wave shaping resistors, load capacitor, lightning impulse, insulation, Electric field.*

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1. INTRODUCTION

In the present scenario, to reduce the gap between demand and generation, power systems reliability is of utmost importance. Reliability of power systems depends on performance of equipment's such as transformers, transmission lines, circuit breakers and insulators. These components are subjected to impulse voltages. Therefore, before keeping these components into service, these are tested to withstand the above voltages. Most common method of generating impulse voltages in laboratory is using Marx generator.

The design, development and work carried out on the Marx generators for generation of lightning impulses, by the earlier researchers are briefly presented. Madhu Palati designed & developed a compact single stage Marx generator to study the lightning characteristics [1]. Madhu Palati discussed the effect of stray capacitance on lightning impulse in an impulse generator [2]. Manuel et al. discussed the importance of wave-shaping resistors in Marx generator [3]. Adrian et al. in their research work used a 20 stage Marx generator for generating 4 MV lightning impulse [4]. Ahmed et al. had designed the low cost, effective, and portable compact 10-stage Marx generator capable of producing lightning impulse voltages of up to 25 kV [5]. Vivek presented the effect of circuit parameters on the impulse have been studied [6]. Apart from lightning impulse generation, Marx generators find extensive application in pulse power application for generation of short rise time pulses like Plasma soft X-ray, High Power Microwave generators, Ion beam material treatment, pollution control, pulsed corona precipitators, ozone production, food processing, water purification and medical applications [7-8] etc.

Lightning impulse wave can be characterized as double exponential wave and is given by

$$V=[\exp(-\alpha t)-\exp(-\beta t)] \qquad (1)$$

Where α and β are constants and Vo is the charging voltage. The impulse voltage in power systems is generally expressed in terms of rise time, fall time and the peak voltage. For impulse wave of 1.2/50 µs the value of α and β are 0.0146 and 2.467 respectively. Standard impulse waveform is shown in Fig.1

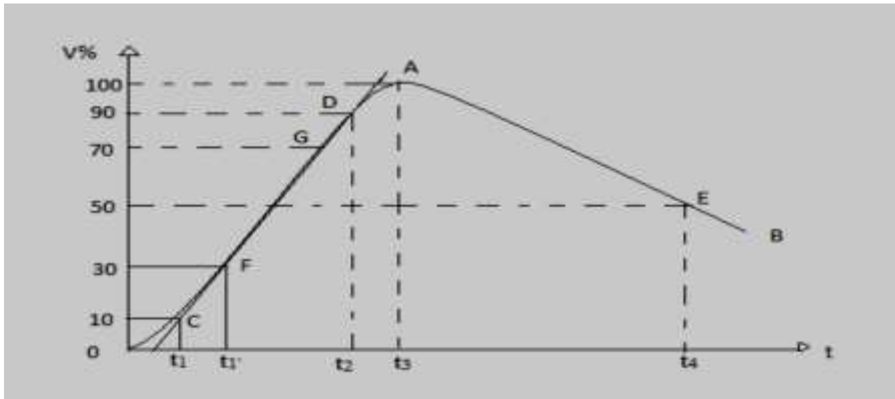

Fig-1: Standard Lightning Impulse

In Fig.1, point A corresponds to 100% peak value. Sometimes the origin O will not be visible. Therefore, O_1 is treated as virtual origin. Standard tolerance allowed for front time is ±30% and that of tail time is ±20%.

In the present work, attempts have been made to design, analyze and fabricate wave-shaping resistors and load capacitor for a given 200 kV Marx generator. Simulation has been carried out in PSPICE to compare with experimental waveform. Also, design of high voltage cylindrical capacitor and estimation of electrical field in the dielectric is performed using ANSYS software.

2. ESTIMATION OF MARX PARAMETERS

Front time, tail time, peak voltage, efficiency and energy are estimated for a given Marx of ten stages, each stage capacitor of rating 10nF, 20 kV. For generating standard lightning impulse of 1.2/50µs, wave shaping resistors and load capacitance are estimated. When Marx is erected all capacitors get connected in series and the total erected capacitance or equivalent capacitance C_1 of the Marx is given by

$$C_1 = \frac{C}{n} = \frac{10\,nF}{10} = 1\,nF \qquad (2)$$

For generation of lightning impulse, the ratio C_1/C_2 lies between 6 and 106.5 [9,10].

Where C_2 is the Load Capacitance.

In the present work, the above ratio is taken as 10. Therefore, C_1/C_2=10 and C_2=1nf /10 = 100pF

Time to front is given by

$$T_1 = 3\,R_1 \times \frac{C_1 C_2}{C_1 + C_2} \qquad (3)$$

Substituting T_1=1.2µsec, C_1=1nF and C_2= 100 pF in (3)

$$1.2 \times 10^{-6} = 3R_1 \frac{(10^{-9} \times 100 \times 10^{-12})}{(10^{-9} + 100 \times 10^{-12})}$$

R_1 = 4610.5 Ω

Time to tail is given by

$$T_2 = 0.7(R_1+R_2)\,(C_1+C_2) \qquad (4)$$

Substituting, C_1=1nF and C_2= 100 pF and R_1 =4610.5 Ω in (4)

$$50 * 10^{-6} = 0.7(4610.52 + R_2) \times (10^{-9} + 10^{-10})$$

R_2 = 60621 Ω

Efficiency of Marx is given by

$$\eta = \frac{C_1}{C_1+C_2} \times \frac{R_2}{R_1+R_2} \qquad (5)$$

Substituting the above values in (5), the efficiency obtained is 84.86%.

The no load output voltage V_o of Marx is given by

$$V_o = \eta \times n \times V \quad (6)$$

Substituting, efficiency $\eta = 84.86\%$, n= number of stages=10 and voltage to which the stage capacitor is charged=20kV in (6), V_o =169.7 kV.

Energy of Marx is given by

$$E = \frac{1}{2} * C * V^2 = 20\,J \quad (7)$$

3. SIMULATION OF LIGHTNING IMPULSE

The schematic circuit and the simulated output waveform are shown in Fig.2 (a) and Fig.2 (b). Due to unavailability of voltage divider circuit and limitation of Tektronix High voltage probe P6015, high voltage pulses upto 45 kV can be measured. Therefore, to verify the simulation results with experimental results, the Marx was charged to 4.5 kV. From Fig.2 (b), the rise time, tail time and peak voltage for the impulse waveform are 1.14 µs, 46.2 µs and 37.6 kV respectively. Both the rise time and tail time are well within the limits and are in close agreement with standards [11]. There is merely 1.5% difference in the estimated value and the simulated value. Both the results are closely matching.

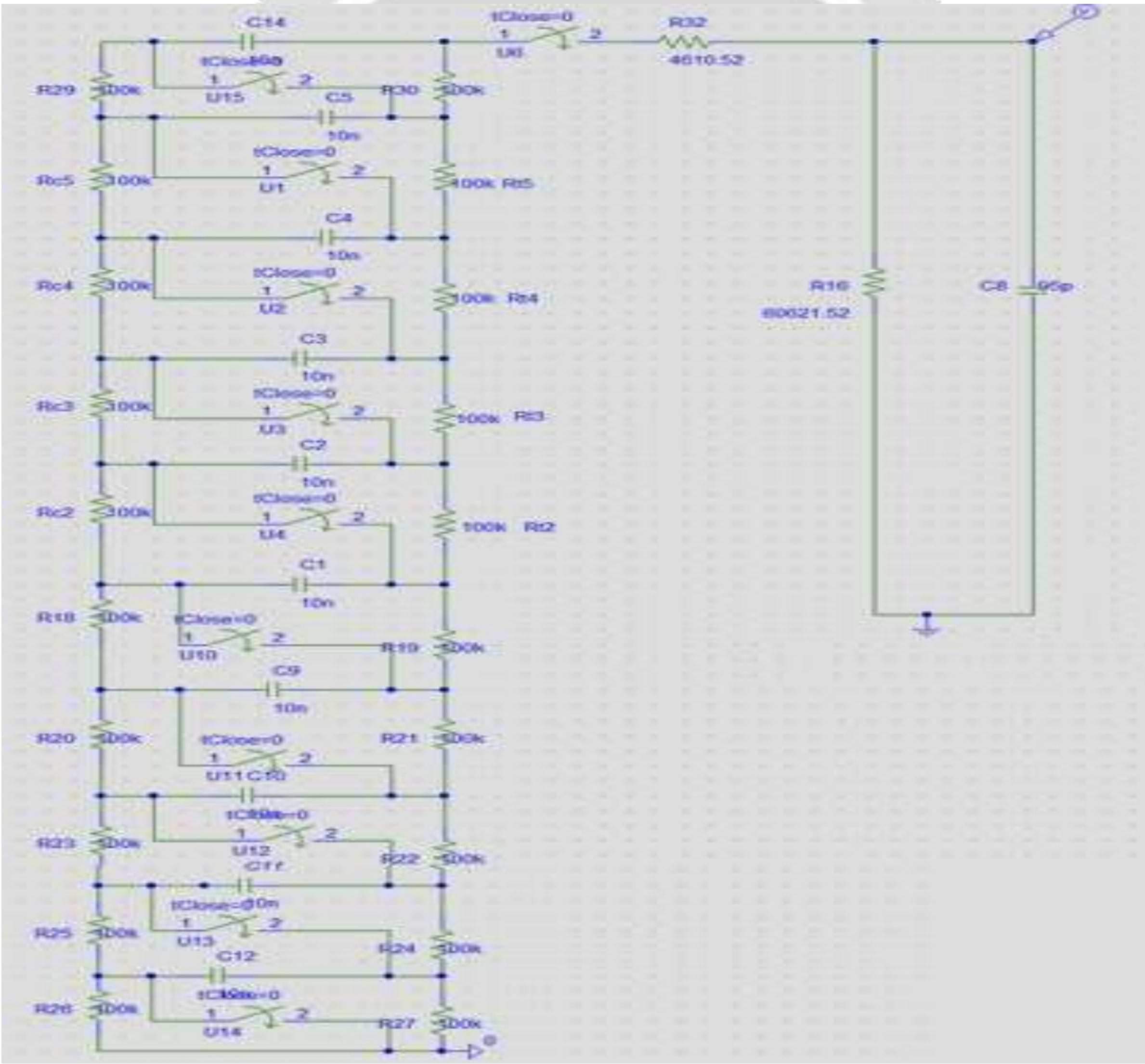

Fig-2(a): Schematic circuit of 10 stage Marx

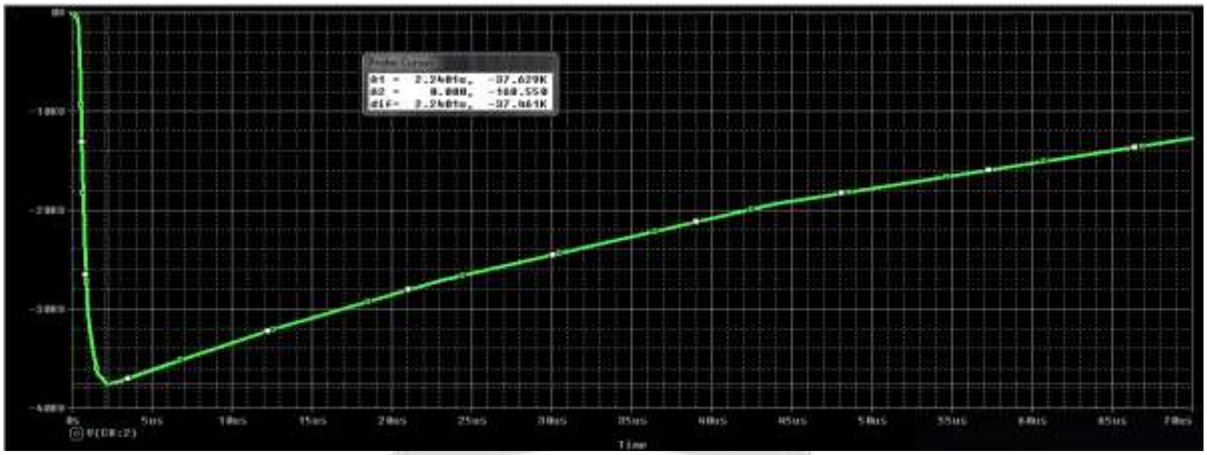

Fig-2(b): PSPICE voltage waveform of Lightning impulse

4. EXPERIMENTATION AND DISCUSSIONS

4.1 Fabrication of wave-shaping resistors

The Estimated value of Front resistor is 4610.5Ω. R_1 is composed of 46 resistors of each 100Ω, all connected in series combination to get the required resistance. The Estimated value of Tail resistor is 60.6 kΩ. R_2 is composed of 45 resistors of each 1kΩ, all connected in series combination with three resistors of each 5 kΩ resistors. The assembled model of front resistor and tail resistor are shown in Fig.3(a) and Fig.3(b) respectively.

Fig-3(a): Arrangement of Front Resistor (R_1)

Fig-3(b): Arrangement of Tail Resistor (R_2)

4.2 Fabrication of 100 pF, 80 kV Load capacitor

The desired Load capacitance is 100 pF. The limitation of P6015 probe is it can measure voltage upto 45 kV. Therefore, taking safety factor into consideration, the load capacitor was designed to withstand upto 80 kV. C_2 is composed of 20 capacitors of each 1000pF, 4 kV rating, all connected in series combination and this gives a capacitance of rating 50pF, 80kV. Therefore, two sets of the above combination were connected in parallel as shown in Fig.4 to get the required load capacitance of 100pF. The measured value of load capacitance using LCR meter is 95Pf

Fig-4: Arrangement of load capacitor (C_2)

4.3 Experimentation

The Experimental set up of Marx with Wave shaping resistors, load Capacitance & DSO is shown in Fig.5(a). The Power supply is switched on and the by adjusting the variac the output voltage of HV transformer is set to 4.5 kV. This voltage gets applied across all the stage capacitors. The gap between the sphere gaps is set in such a way that breakdown occurs in the spark gap when the capacitors get charged to 4.5 kV. During erection, all the capacitors get connected in series and discharge into the load circuit, generating a lightning impulse wave across the load circuit. The impulse waveform across the load circuit is captured by using Tektronix DSO 3034 and is shown in Fig.5(b).

Fig-5(a): Marx set up with wave shaping resistors and load Circuit

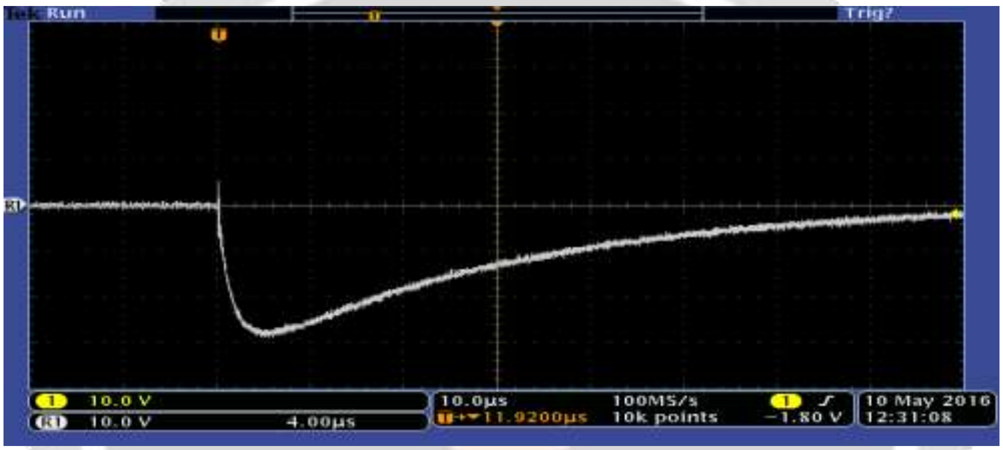

Fig-5(b): Lightning impulse output waveform

From Fig.5 (b), the rise time and tail time are 1.25 µs and 26 µs respectively. Tektronix 6015 HV probe is having a multiplication factor of 1000. Therefore, the peak voltage obtained is 2.9 divisions, each division is of 10V and multiplication factor of 1000 gives 29kV. The rise time obtained from the waveform (1.25µs) is in close agreement with standard value 1.2µs and well within the tolerance value of ±20% [11].

The tail time got affected due to following reasons:

- Stray capacitance of the capacitors
- Internal inductance of the Marx generator
- Inductance of the wave-shaping resistors (each resistor is approximately 5µH).
- Inductance of load capacitor (generally high voltage capacitors possess internal inductance)
- Change in the tail resistance value (can be due to internal flashovers between the series combination of resistors)

4.4 Design of 100pF, 200kV cylindrical capacitor

In the Present work, attempt has been made to design a cylindrical capacitor with inner & outer electrodes in the form of hollow stainless steel cylinders of suitable diameters & length to realize required capacitance and adequate dielectric strength. The capacitance of a cylindrical capacitor of length l, diameters of inner and outer electrodes a & b respectively, is given by

$$C = \frac{2\pi\varepsilon_0\,\varepsilon_r}{\ln\left(\frac{b}{a}\right)} * l \qquad (8)$$

Where C is the capacitance in farads, ε_o is absolute permittivity of free space =8.854 x 10^{-12} F/m, ε_r is the relative permittivity of the dielectric medium of capacitor, l is the length of the cylindrical capacitor, b is the diameter of the outer electrode, & a is the diameter of the inner electrode.

In the present work, Perspex with ε_r =3.3 and breakdown strength of about 16kV/mm (rms) under 50 Hz voltages has been chosen as the dielectric for the capacitor. The breakdown strength under very fast (sub-nanosecond) pulses will be much higher, possibly 25kV/mm to 30kV/mm [12]. Considering all the above, the following dimensions have been worked out:

C = 100 pF, b= 122 mm (available), and l= 300 mm in (8), we get inner diameter of cylinder a = 70mm

The maximum electric field is given by

$$E = \frac{2V}{a\ln\left(\frac{b}{a}\right)} = \frac{2*200kV}{70*\ln\left(\frac{122}{70}\right)} = 10.3\ kV/mm \tag{9}$$

Here, V is the nominal no-load output voltage of the Marx and for the present case, V=200kV giving Emax ≈ 10.3 kV/mm which is quite safe compared to the reported breakdown strength of 25 kV/mm [12].

Insulation design is an important aspect in designing a high voltage capacitor. It is very much essential to avoid the unwanted flashover between the two electrodes. The estimation of electric field is carried out using ANSYS software and is shown in Fig.6. From Fig.6 the maximum electric field is 9.9kV/mm and the difference is merely less (3.7%), this verifies the method of validation.

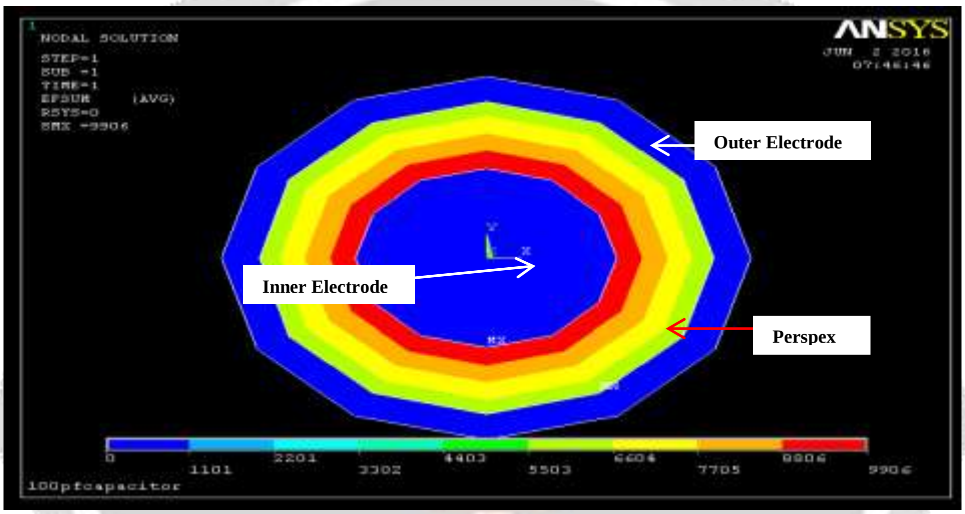

Fig-6: Electric field distribution in a cylindrical capacitor

5. CONCLUSION

In this paper, studies on lightning characteristics of 200kV Marx generator were carried out. The wave shaping resistors and load capacitance were designed and fabricated for the existing Marx at our laboratory. Simulation and experiments were carried out on the above Marx. Front time is well within the limits, tail time was different because of stray capacitance, inductance of wave shaping resistors, load capacitor & Marx inductance and flashover between wave shaping resistors. Better wave shape can be achieved by providing sufficient spacing between the resistors to avoid flashover between resistors, replacing the wire wound resistors with non-inductive and reducing the effect of stray capacitance. Design and analysis of 100pF, 200kV load capacitor was carried out and Estimation of Electric field is carried out on the designed model using ANSYS software. Both theoretical and simulation values matched closely.

6. ACKNOWLEDGEMENT

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