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Characterization of Marx Generator

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This paper discusses the characterization of 200 kV, 20 J mini Marx generator. Marx generators are extensively used in very high voltage fast pulse generation. Capacitors are the major components of Marx generator, apart from the capacitance of the capacitor the other parameters such as internal inductance (Equivalent series Inductance) and Equivalent series resistance (ESR) has significant effect on the output current waveform. The internal inductance of the capacitor, ESR and the discharge path to the load circuit has to be kept as minimum as possible so as to achieve lower characteristic impedance, higher peak current, faster rise time and reduced Full Width Half Maximum(FWHM). Therefore there is a need to determine the internal inductance and ESR of Marx generator. Short circuit discharge test is conducted on the Marx generator to determine the value of total inductance of Marx generator during erection. From the determined value of total inductance of Marx generator L_T and erected capacitance of the Marx C_T, ESR is estimated from the PSPICE circuit. Also maximum output of Marx is estimated using the PSPICE circuit.

Key Words: *Marx generator, Capacitor, Equivalent series inductance, Equivalent series resistance, Full Width Half Maximum, characteristic impedance, Short circuit discharge, PSPICE software.*

1.0 INTRODUCTION

The Main aim of pulsed power engineering is to obtain very short pulses of very high power levels, greatly minimizing the energy losses (which depend on time duration) and achieving required objective of very high energy intensity in the load. Pulsed power engineering has found many applications of great importance in areas of defense, nuclear physics, civilian, industrial and medical [1-4] etc.

In all the above applications, Marx generator is the primary source of pulsed voltage/current. The Marx generator [5] (proposed by Prof. Erwin Marx in 1923 at the Technical University of Braunschweig, Germany) works on the principle of charging several capacitors in parallel and discharging them in series so that voltages add up. Most commonly, Marx generators are used to generate double exponential standard Impulse voltage waves of 1.2µs/50µs shape(to represent lightning) and voltages of 250µs/2500µs shape (to represent switching over voltages in power system) in laboratories for testing of High voltage power system equipments/ components such as transformers, cables and insulators. In conventional Marx generators the internal inductance of the Marx is not of much importance. In several applications, the time interval between 50% point of the front and tail is of great importance. This time interval is usually referred to "Full width at Half Maximum" or FWHM Usually the required values of FWHM are much less than 0.5 µs. This implies that the time from zero to the peak is of the order 0.1 µs.

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To achieve this there are two possibilities. Firstly the capacitance of the Marx can be reduced however this reduces the energy of the Marx and may not be always acceptable. The second option is to reduce the overall inductance of the Marx circuit which has also got some serious practical limitations.

The inductance of the Marx is made up of

(i) L_C : The total internal inductance of all the capacitors in series and

(ii) L_{RP} : The total inductance due to the current flow path including electrode Leads, sparks and current return path

1.1 Internal inductance of capacitor (ESL)

The internal inductance of the capacitor commonly referred as equivalent series inductance and is mainly due to geometric design of capacitor element, length and thickness of the internal lead connections, case design, Insulation design and magnetic flux produced by the discharge current.

1.2 Equivalent Series Resistance (ESR)

When a capacitor is subjected to an ac voltage, some energy is dissipated as heat and hence dissipation factor has to be considered. ESR represents the losses in the dielectric of a capacitor while discharging. Since these losses are finite, ESR will be finite [6]. Dissipation factor is also referred as loss tangent and is defined as tangent of (90-Φ), where Φ is the phase angle between V and I. this difference is caused due to dielectric losses.

The equivalent circuit of a capacitor [7] is represented as shown in Figure 1.

FIG. 1 EQUIVALENT CIRCUIT OF A CAPACITOR

1.3 Inductance due to current flow path

L_{RP} is the total inductance due to the current flow path including electrode consists of two components

(i) Inductance due to the leads of the electrodes of the spark gap and spark path between the spark gap electrodes

(ii) Inductance due to the flux in the loop formed by the forward and return paths of the discharge current.

2.0 DETERMINATION / ESTIMATION OF INDUCTANCE OF 10NF, 20KV CAPACITOR

Inductance is estimated from the known value of capacitance and frequency of discharge current when discharging into a short circuit [7]. The discharge path is a copper strip of shortest possible length & current is measured using a Pearson coil & CRO, the schematic for conducting discharge test is shown in Figure 2. Frequency of discharge is given by equation (1)

$$\mathbf{f_0} \cong \frac{\mathbf{1}}{\mathbf{2\pi\sqrt{L_T C_T}}} \quad ....(1)$$

From the known values of charging voltage, L and C, equivalent circuit of the capacitor during discharging is developed in PSPICE. By trial and error vary the value of ESR in the PSPICE circuit till the experimental and simulated discharge output waveform match very closely and these two waveforms to be closely identical in terms of current magnitude and the time period of each cycle.

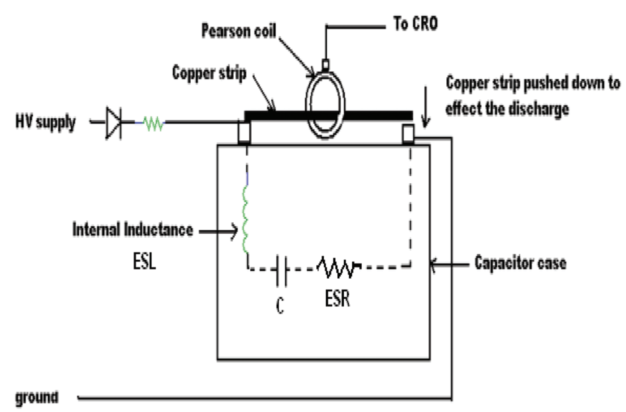

FIG. 2 SCHEMATIC FOR OBTAINING THE DISCHARGE CURRENT TO DEDUCE THE INTERNAL INDUCTANCE

2.1 Short circuit discharge on a 10nF, 20kV capacitor

The short circuit discharge test on a 10 nF, 20 kV Capacitor is carried out by the procedure explained in section 2. The experimental set up is for short circuit discharge on a 10nF, 20 kV capacitor is shown in Figure 3(a). The output current wave form is captured on the DSO screen and is shown in Figure 3(b). From the discharge waveform shown in Figure 3(b), the time period for one cycle is 375 ns. Substituting the values of frequency (2.67 MHz), capacitance (10 nF) in the equation (1), we get L=0.36 µH. Using the values of circuit inductance L, equivalent capacitance C and charging voltage, equivalent circuit of the Capacitor during short circuit discharging is developed in PSPICE and by trial and error the value of ESR is 0.1 Ω. The PSPICE current waveform is shown in Figure 3(c).

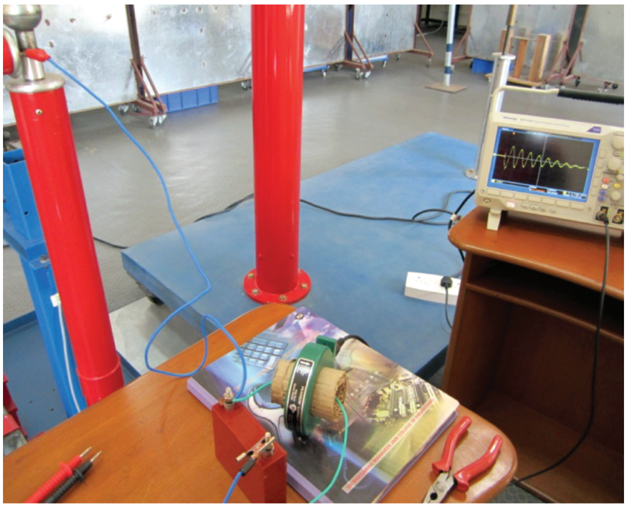

FIG. 3 (A) EXPERIMENTAL SETUP FOR SHORT CIRCUIT DISCHARGE ON A 10NF, 20KV CAPACITOR

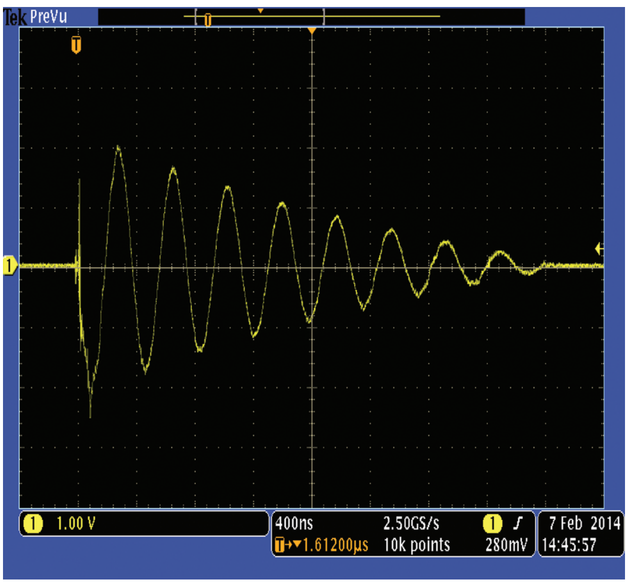

FIG. 3 (B) DISCHARGE WAVEFORM OF 10NF, 20KV CAPACITOR

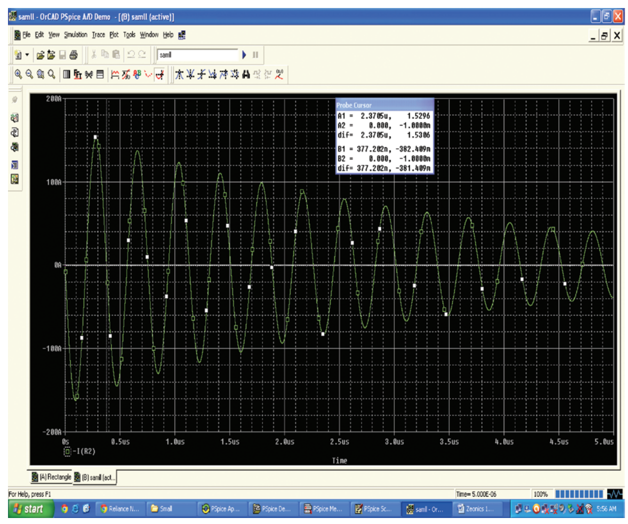

FIG. 3 (C) PSPICE OUTPUT CURRENT WAVEFORM OF 10NF, 20KV CAPACITOR

The experiments are carried out for different discharge path lengths to study the behaviour of the capacitor i.e. effect of inductance on the output current waveform. The inductances obtained for the different discharge path lengths (26cms, 78cms and 158cms) are 0.36 µH, 1.39 µH and 1.83 µH respectively. The inductance versus the discharge path length is shown in Figure 3(d).

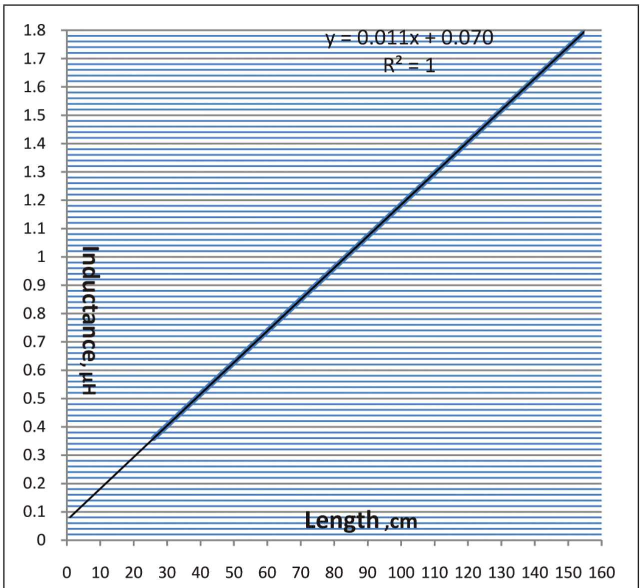

FIG. 3(D) GRAPH SHOWING INDUCTANCE VERSUS DISCHARGE PATH LENGTH OF 10NF, 20KV CAPACITOR

The minimum discharge path length including the lead connections of the capacitor with respect to the return path is 13cms. By extrapolating the graph at zero length the internal inductance is

0.06 µH. practically for any capacitor, there exists a minimum discharge length due to its internal lead connections, for this capacitor the minimum discharge length is 13cms. By adding a trend line to the graph in Excel sheet, the inductance of the Capacitor at this discharge length (from trend line equation y = ((0.011x13) + 0.07) is approximately 0.21 µH. This is the total internal inductance of the Capacitor with shortest discharge path

3.0 DETERMINATION / ESTIMATION OF INDUCTANCE OF 200 kV, 20 J MARX GENERATOR

The short circuit discharge test on 200 kV, 20 J mini Marx generator is carried out by the procedure explained in section 2. The experimental set up is shown in the Figure 4(a) and the Marx is charged to a stage voltage of 4.5 kV.

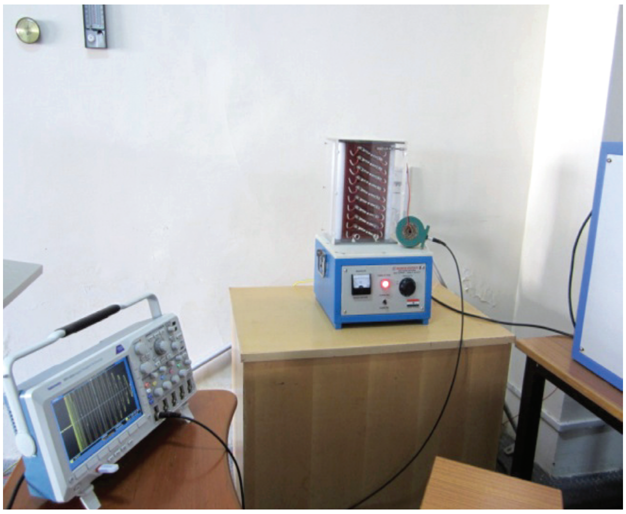

FIG. 4 (A) EXPERIMENTAL SET UP FOR CONDUCTING SHORT CIRCUIT DISCHARGE TEST

The output current wave form is captured on the DSO screen and is shown in Figure 4(b). From the discharge waveform shown in Figure 4(b), the time period for one cycle is 300 ns and the value of frequency is 3.33 MHz, The equivalent capacitance of the Marx Generator during discharging is given by $C_{eq} = \frac{C_{stage}}{n} = \frac{10\ nF}{10} = 1nF$, Where C_{eq} is the equivalent capacitance of Marx while discharging, C_{stage} is the stage capacitance and is equal to 10 nF and n is number of stages and is equal to10.

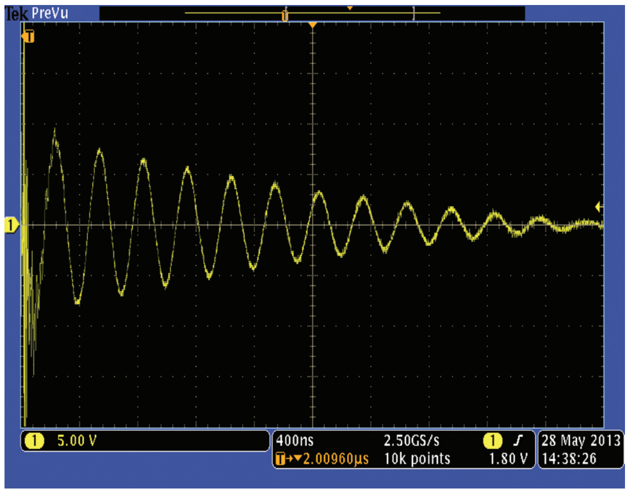

FIG. 4 (B) SHORT CIRCUIT DISCHARGE CURRENT WAVEFORM OF MARX GENERATOR

Substituting the values of f=3.33 MHz and C_{eq} =1nF in equation (1), Total Marx circuit Inductance L_{eq} is obtained and is approximately equal to 2.3 µH. Using the values of total Marx circuit inductance L_{eq}, equivalent capacitance C_{eq} and charging voltage, equivalent circuit of the total Marx during discharging is developed in PSPICE and is shown in Figure 4(c).

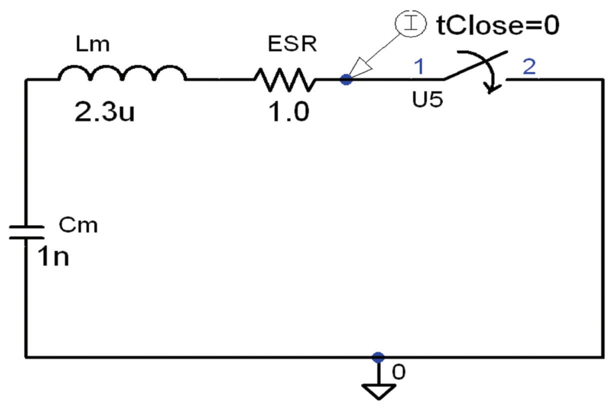

FIG. 4 (C) EQUIVALENT CIRCUIT OF MARX GENERATOR DURING SHORT CIRCUIT DISCHARGE

By trial and error for the value of ESR equal to 1 Ω the PSPICE output waveform shown in Figure 4(d) closely matches with experimental waveform Figure 4(b) in terms of magnitude and time period at different intervals.

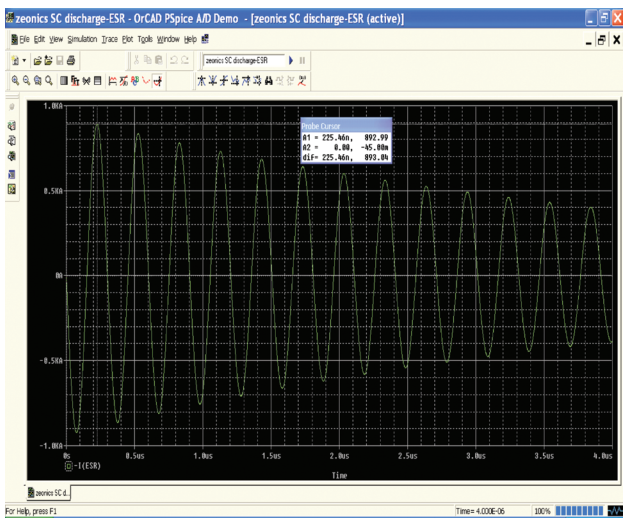

FIG. 4 (D) PSPICE OUTPUT WAVEFORM OF MARX GENERATOR

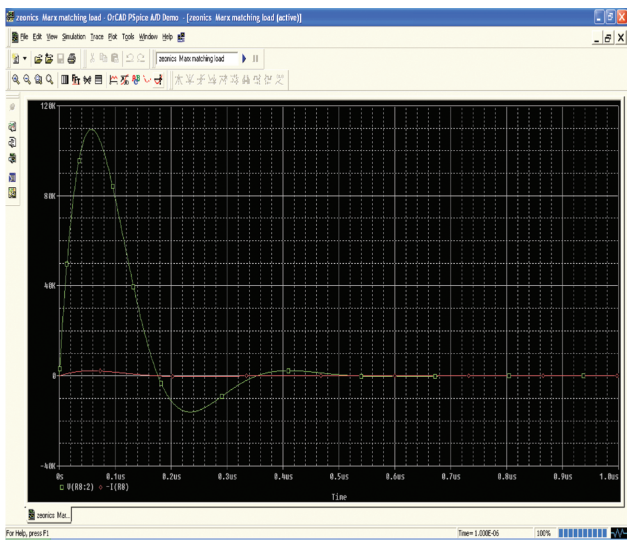

FIG. 5 (B) PSPICE OUTPUT WAVEFORM OF MARX WITH MATCHED LOAD

4.0 MARX OUTPUT WITH MATCHED LOAD

The characteristic impedance of the Marx generator is calculated by the expression shown in equation (2) and the equivalent circuit of Marx with matching load is shown in Figure 5(a).

$$Z = \sqrt{\frac{L_{eq}}{C_{eq}}} = \sqrt{\frac{2.3\mu H}{1nF}} = 48\Omega \qquad ....(2)$$

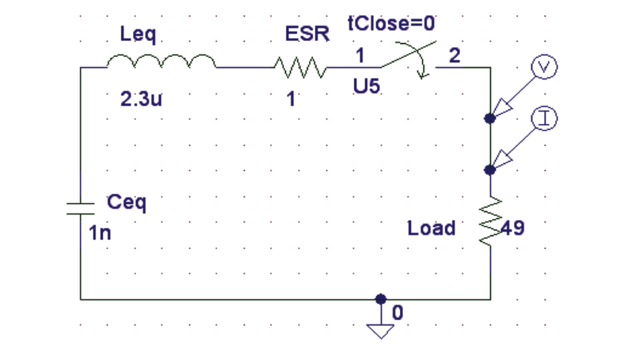

FIG. 5 (A) EQUIVALENT CIRCUIT OF MARX WITH MATCHED LOAD

Maximum output is achieved when the load impedance matches with the Marx characteristic impedance. The total load impedance including the ESR of Marx (1Ω) is 49 Ω.

From the PSPICE output waveform shown in Figure 5(b) the output voltage is 109 kV, rise time is 57.45 ns, output current is 2.23 kA and FWHM is 104.6 ns.

5.0 CONCLUSIONS

The estimated ESR for a single capacitor is 0.1 Ω and total ESR for a Marx generator of ten stages is 1 Ω (for one capacitor it comes to 0.1 Ω which is matching with the estimated value of single capacitor). The estimated inductance of each capacitor is 0.21 μH (for ten capacitors it is 0.21 μH x 10 =2.1 μH) and total inductance of Marx generator of ten stages is 2.3 μH. The difference (2.3 μH – 2.1 μH) is 0.2 μH, which is due to the additional inductance of the connecting lead used to short circuit the HV output of the Marx to the ground terminal. The output of Marx in terms of increase in peak current, reduced rise time and reduced FWHM can be achieved with low characteristic impedance. Since the capacitance is of the capacitors is fixed, low characteristic impedance of Marx is achieved with low inductance. Also we do not have a control over the internal inductance of the capacitors as the design of capacitor and construction is done at the manufacturer company, only possibility is to reduce the discharge path length and use copper strips instead of connecting leads for connecting the load terminals. This information is necessary for an engineer to do further studies in improving the performance (fast rise time, high output current) of the Marx generator.

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