ESTIMATION OF INTERNAL INDUCTANCE & EQUIVALENT SERIES RESISTANCE OF HIGH VOLTAGE CAPACITORS AND BEHAVIOUR OF ARC RESISTANCE

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Abstract: *In this Paper estimation of internal inductance and equivalent series resistance (ESR) of high voltage capacitors is presented. During experimental determination of the above by short-circuit discharge, arc resistance enters the picture and its behavior has also been studied and presented. Four capacitors of different makes & ratings have been studied.*

Key words: *internal inductance, equivalent series resistance, arc resistance, and short circuit discharge current.*

1. INTRODUCTION

Marx generators are used almost routinely as primary sources of pulsed voltage/current in pulsed power applications like particle beam generators[1-2], linear induction accelerators [3], directed energy weapons [4], pollution control, waste water treatment, water purification, food processing, medical applications etc; [5-7]. Capacitors are the most important components of a Marx generator. Other than the capacitance of the capacitors, the other parameters of importance in pulsed power applications are the internal inductance and equivalent series resistance (ESR) of the capacitors. Lower values of internal inductance and ESR aid in achieving lower characteristic impedance, higher magnitude of output current, faster rise time and reduced Full Width Half Maximum (FWHM). Therefore there is a need to characterize capacitors in terms of internal inductance & ESR when intended for use in pulsed power applications. Capacitance value is of primary interest but it can be measured easily using standard techniques and therefore not discussed.

High voltage capacitors invariably consist of many lower voltage elemental capacitors connected in series and/or parallel to achieve required higher working voltages & capacitance values. The interconnections and leads (of terminals) contribute to the finite internal inductance of the capacitor [8]. Further, considering ac excitation, in an ideal capacitor, the current leads the voltage by 90^o. In a real capacitor, some energy is always absorbed by the dielectric to aid rotation of dipoles and appears as heat. Equivalent series resistance represents this loss [9] in the dielectric. The loss angle δ makes the current to lead the voltage by an angle (90-δ) instead of 90^o.The equivalent circuit of a capacitor can therefore be represented as shown in fig. 1.

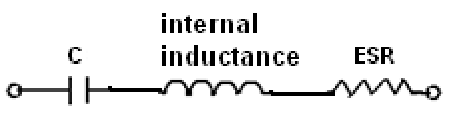

Fig. 1. Equivalent circuit of a Capacitor

2.0 ESTIMATION OF INDUCTANCE OF HIGH VOLTAGE CAPACITORS

Inductance is estimated from the known value of capacitance and frequency of discharge current when the capacitor is discharging into a ‘short circuit’. The short circuit or discharge path is almost invariably a copper strip of shortest possible length. This ‘short circuit’ being a short length of wire/strip, makes its own contribution to inductance. The discharge experiment is carried out by charging the capacitor (HV terminal) to a relatively low voltage and discharge is initiated through a spark between end of the copper strip and LV terminal of the capacitor.

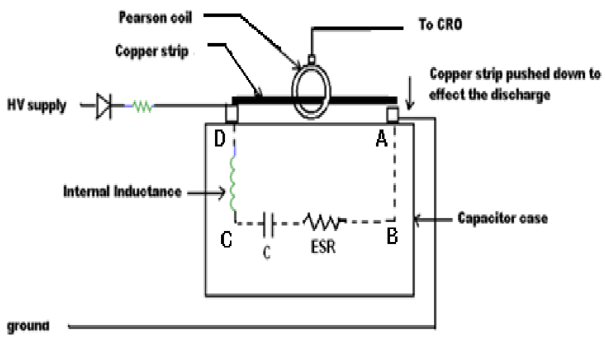

Fig. 2 Schematic for obtaining the discharge current waveform to deduce the internal inductance

One end of the copper strip is connected solidly to one terminal, D, fig 2, the high voltage terminal of the capacitor under test. A small gap is left between the other end of the copper strip and the other terminal A, low voltage/ground terminal of the capacitor. The capacitor (terminal D) is connected to a voltage source through a high resistance (say 1MΩ) and charged to a voltage V by raising the voltage gradually from 0. Now, using an insulating rod, the copper strip near terminal A of the capacitor is pushed sharply towards A. As the gap reduces sufficiently, a spark occurs and the capacitor discharges through the spark and the copper strip. The discharge current is recorded oscillographically using a Pearson coil.

The frequency of the discharge waveform is given by

$$f_O \cong \frac{1}{2\pi\sqrt{L_P\, C}} \qquad \text{---------} \ (1)$$

From the known value of C and f_O (obtained from the discharge current oscillogram), the preliminary value, L_P of internal inductance is obtained using equation (1). As ESR will be finite, the discharge current will be a damped sine wave. Now, assuming a reasonable value for ESR, less than 1Ω, and the values of C & L_P, the discharge current waveform is obtained by simulation using PSPICE. The value of ESR is now varied in steps in the PSPICE simulation to achieve a close match between the experimental & PSPICE discharge current waveforms [10].

3.0 SHORT CIRCUIT DISCHARGE TEST ON HIGH VOLTAGE CAPACITORS

Short circuit discharge experiments were conducted as described above on high voltage capacitors of four different types to estimate their internal inductances and ESR. The schematic of the experimental set up for conducting the short circuit discharge test [11] is shown in fig.2. The capacitors are listed below:

- 0.1µF, 10 kV, (Type 1)
- 0.01µF, 10 kV, (Type 2)
- 0.01µf, 20kV, (Type 3)
- 0.15 µF, 50kV, (Type 4)

The experimental and PSPICE simulation discharge current waveforms for the above capacitors are shown in figures 3 to 6. The preliminary values of all the four types of capacitors internal inductances are calculated using the frequency of the experimental discharge current waveforms and equation (1). The values are 358nH, 369nH, 399nH and 112nH respectively.

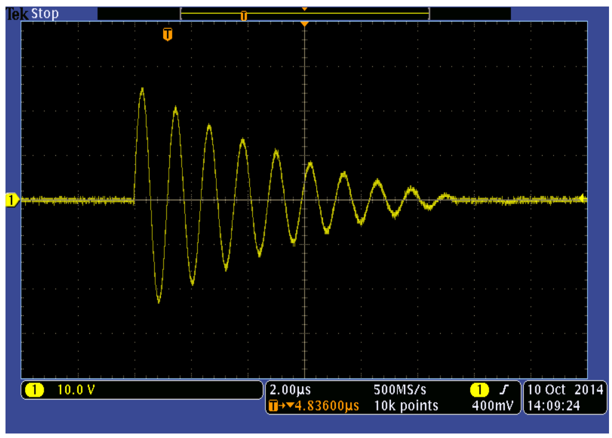

Fig. 3(a). Experimental Short circuit discharge waveform of type 1 capacitor

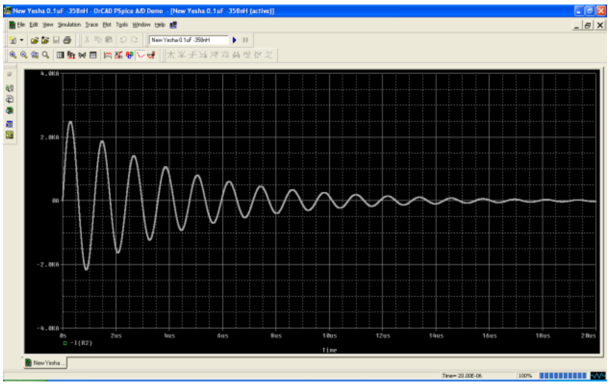

Fig. 3(b) PSPICE output discharge waveform of type 1 capacitor

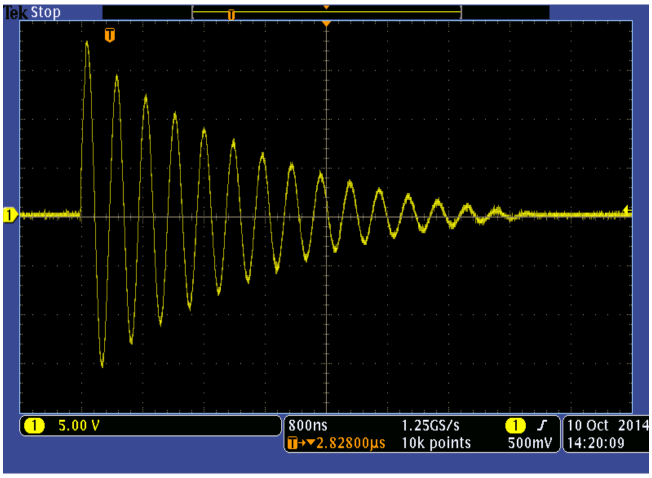

Fig. 4(a). Experimental Short circuit discharge waveform of type-2 capacitor

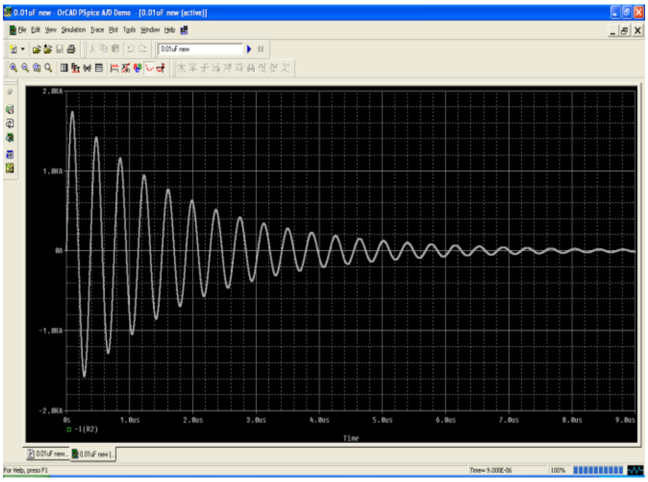

Fig. 4(b). PSPICE output discharge waveform of type-2 capacitor

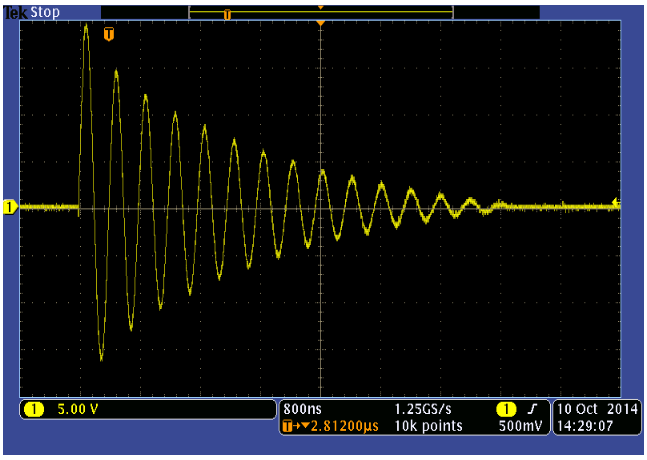

Fig. 5(a). Short circuit discharge waveform of type-3 capacitor

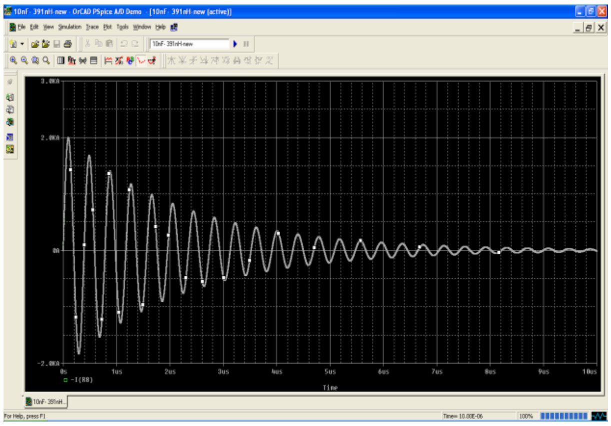

Fig. 5(b). PSPICE output discharge waveform of type-3 capacitor

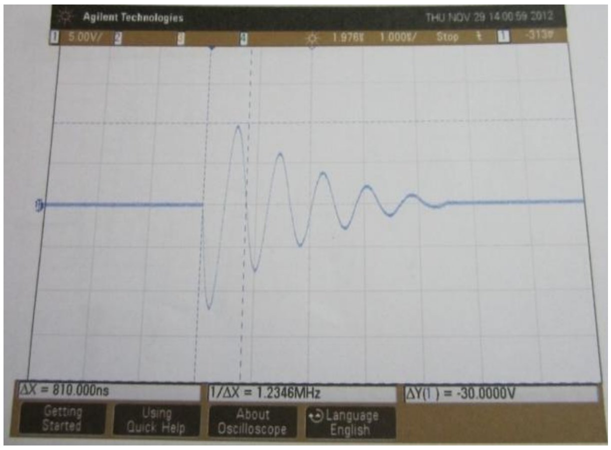

Fig. 6(a). Experimental Short circuit discharge waveform of type-4 capacitor

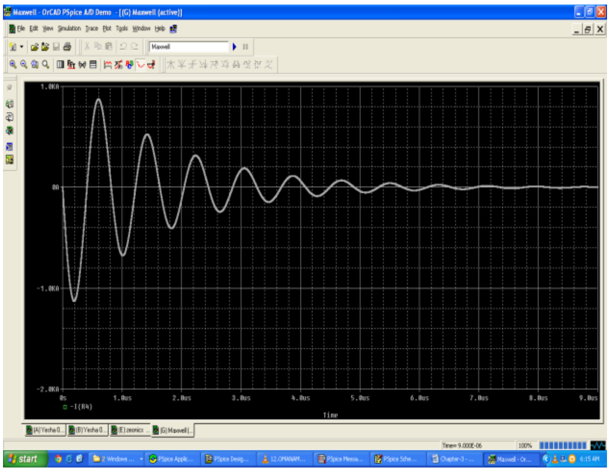

Fig.6(b). PSPICE output discharge waveform of type-4 capacitor

When evaluating the value of ESR by matching experimental and PSICE waveforms, it was found that a single value of resistance was not adequate. Therefore, resistance values were varied in PSPICE simulation to obtain current peaks matching with the 1st, 2nd, 3rd, 4th,.. positive peaks of experimental discharge current waveform. It was found that these resistance values increased with reducing current (i.e. successive peaks). The resistance values are given in Tables 1 to 4 for the four capacitors.

Table-1 Experimental positive peak currents and corresponding resistances of Type-1 capacitor

Experimental current		**Resistance, ohms**
Peak No	**Amps**	
1st	2550	0.1
2nd	2100	0.11
3rd	1700	0.11
4th	1350	0.115
5th	1100	0.115
6th	800	0.127
7th	650	0.127
8th	450	0.138
9th	300	0.15
10th	200	0.16

Table-2 Experimental positive peak currents and corresponding resistances of Type-2 capacitor

Experimental current		**Resistance , ohms**
Peak No	**Amps**	
1st	1780	0.28
2nd	1480	0.31
3rd	1250	0.31
4th	1060	0.31
5th	900	0.31
6th	760	0.31
7th	650	0.31
8th	525	0.32
9th	450	0.32
10th	375	0.32
11th	295	0.33
12th	250	0.33
13th	200	0.34
14th	140	0.36
15th	100	0.38

Table-3 Experimental positive peak currents and corresponding resistances of Type-3 capacitor

Experimental current		**Resistance, ohms**
Peak No	**Amps**	
1st	2000	0.2
2nd	1750	0.25
3rd	1500	0.28
4th	1300	0.28
5th	1130	0.28
6th	1000	0.28
7th	850	0.28
8th	750	0.28
9th	640	0.28
10th	550	0.28
11th	480	0.28
12th	400	0.28
13th	350	0.28
14th	300	0.28
15th	230	0.3
16th	200	0.3
17th	150	0.31
18th	100	0.34

Table-4 Experimental positive peak currents and corresponding resistances of Type-4 capacitor

Experimental current		Resistance, ohms
Peak No	Amps	
1st	974	0.1
2nd	615	0.115
3rd	385	0.12
4th	232	0.125
5th	114	0.14

The values of resistances so obtained are plotted as a function of the current magnitudes for all the four types of capacitors and shown in fig. 7.

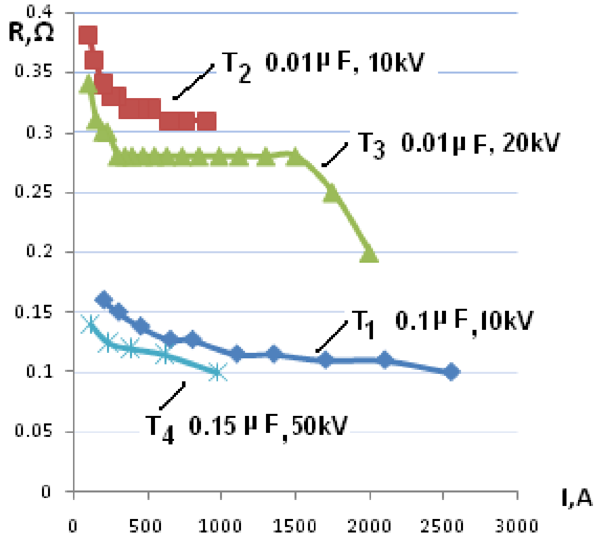

Fig. 7. Current versus Resistance for all capacitors

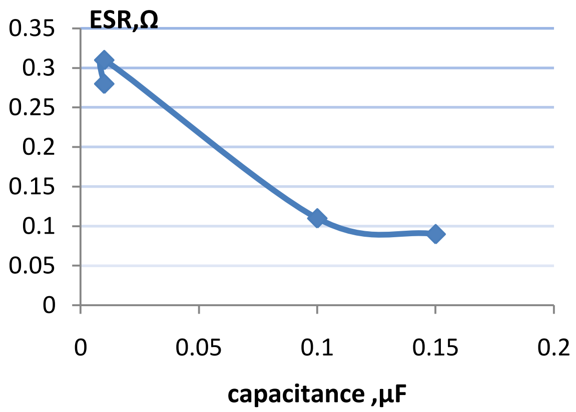

Fig. 8. Capacitance versus Equivalent Series Resistance for all capacitors

4.0 DISCUSSION ON THE BEHAVIOR OF RESISTANCE

Obviously, the variation of resistance with current magnitude cannot be attributed to dielectric losses (energy absorbed by dipole oscillations). The only other possibility is that the resistance of the spark is getting added to the ESR. It is a well known fact that arc/spark resistance varies inversely & nonlinearly with current [12-14]. Therefore the resistance evaluated is the sum of spark resistance & ESR. The overall pattern is that

(a) The resistance reduces from a high value at low currents (≈ 100A) and more or less stabilizes at around 250A. It may be concluded that below 250A, the spark channel resistance is substantial.

(b) Above 250A, the spark channel resistance is practically negligible and the stabilized value would be substantially the ESR of the capacitor.

(c) The ESR is high for low value capacitors & vice versa. Obviously, higher value capacitors, irrespective of voltage, would have larger number of capacitor elements in parallel and hence the ESR of the elements also in parallel, thereby bringing down the ESR. Capacitors Type 1 & Type 4 show this. Conversely, low value capacitors, such as Type 2 & Type 3, irrespective of voltage rating, have higher values of ESR.

(d) From the limited data available, the ESR values taken as the approximate stabilized values (beyond 500A) from fig.7 have been plotted in fig.8. From this, for currents in the kA range and for capacitors of 0.1μF or higher the ESR is likely to be 0.1Ω or perhaps even lower.

(e) The data of spark gap resistance & ESR can be used as guidance values when designing multistage fast Marx generators in pulsed power applications having critical specifications.

(f) In equation (1) & section (3), the estimates of internal inductance were designated as preliminary values. By including the resistance values (spark path resistance + ESR) in PSPICE simulations, the inductance values were re-estimated and, as may be expected because of the low values of resistance, remained substantially the same.

Therefore the preliminary values may now be considered as substantially correct values.

5.0 CONCLUSION

In this present work, the internal inductances & equivalent series resistances of four different capacitors of different ratings have been estimated. From the experimental data of short-circuit discharge currents, the behavior of spark-path resistance as a function of discharge currents has been studied. This enables the true ESR values to be arrived at. It is believed that these will be of use in more accurately assessing the output current characteristics of multistage, low energy, fast Marx generators.

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