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Challenges in Measurement of Low-Value ESL and ESR of High-Performance PFN Capacitors for Klystron Modulator

M. Acharya[1*], J. K. Mulchandani[1], Prem Baboo[1], T. Reghu[1], Ravindra K. Sharma[2], Y. Wanmode[1], Vivek Sanadhya[2], V. Kurariya[2], M. Lad[1], Anuradha Mayya[2] and P. Shrivastava[3]

[1]RFSD, Raja Ramanna Centre for Advanced Technology, Indore - 452013, Madhya Pradesh, India; macharya@rrcat.gov.in

[2]CnID, E and I Group, Bhabha Atomic Research Centre, Mumbai - 400094, Maharashtra, India

[3]PAG, Raja Ramanna Centre for Advanced Technology, Indore - 452013, Madhya Pradesh, India

Abstract

In the high voltage line type pulse modulators, Pulse Forming Network (PFN) capacitors are one of the important components. These capacitors operate at peak kilo ampere current range and at repetition rate in the range of a few hundred hertz. The performance of these capacitors is critical w.r.t. overall system performance, and they are required to operate at high power density and low losses with high reliability. The Equivalent Series Inductance (ESL) and Equivalent Series Resistance (ESR) are two critical parameters that affect the performance of these capacitors. PFN modulator demands a capacitor of very low ESL and ESR for reliable operation and generation of high-voltage pulses. Higher ESR value adversely affects the performance of the capacitor by raising its temperature and thus deteriorating its life. ESL value does not directly affect life, but it affects the quality of high voltage pulse. In RRCAT, the PFN capacitors purchased from Indian manufacturers were showing high-temperature rise and failures. Therefore, new capacitors were designed to have lower ESL and ESR values. Measurement of ESL and ESR is important to evaluate the performance of the capacitors. The low value of these parameters makes their measurement a challenging task and requires special techniques. For low values of ESL and ESR (less than 100 mΩ) measurement, a differential measurement technique was used in which modification and different layouts were explored to improve the repetitive accuracy of the measurements. The differential ESR and ESL measurement techniques with more emphasis on the low-value ESR measurement will be discussed in the paper.

Keywords: High Voltage Energy Storage Capacitors, Klystron Modulator, Pulse Forming Network

1. Introduction

Klystron amplifiers are widely used in high-power RF applications like particle accelerators and radar systems. The key component in the RF system is the high-voltage pulse modulator, which provides the necessary high-voltage pulses for the klystron. Line-type modulators are commonly used for generating these high-voltage pulses. The Pulse Forming Network (PFN) capacitors are crucial components within the modulator, as they greatly impact its overall performance and reliability. PFN capacitors, along with an inductor, form a pulse-forming network that gets charged at high voltage and then discharged through a thyratron and pulse transformer to produce the high-voltage pulses required by the klystron. It is essential to measure certain parameters of these capacitors that significantly affect both the circuit's performance and the lifespan of the capacitors. Two critical parameters to measure are the Equivalent Series Inductance (ESL) and the Equivalent Series Resistance (ESR) of the capacitors. The ESL value determines the resonant frequency and impedance of the capacitor, while the ESR value affects

**Author for correspondence*

its heat dissipation and overall longevity. So the accurate measurement of ESL and ESR is very crucial for pulse modulators. These measurements provide valuable insights into the behavior of the capacitors and help in designing robust and efficient pulse-forming networks for klystron-based RF systems.

In RRCAT, a line type of modulator-fed klystron-based microwave system has been deployed for the Radiation Processing Facility. However, the PFN capacitors purchased from local manufacturers exhibited high-temperature rise and failures. Consequently, the development of capacitors with improved designs was undertaken to reduce failures. To assess the performance improvement of these capacitors compared to earlier versions, measurements of important parameters were required. This paper discusses the ESL and ESR measurement techniques employed for these capacitors.

2. Description

A new capacitor with an improved design was developed, and its performance was assessed by measuring its Equivalent Series Inductance (ESL), Equivalent Series Resistance (ESR), and heating temperature. Various measurement techniques are available for determining the ESL and ESR values of capacitors. However, standard LCR instruments are not suitable for this measurement since the capacitors used in the Pulse Forming Network (PFN) need to have low ESR values in the range of tens to hundreds of milliohms.

A widely used method for measuring the ESL and ESR of capacitors is the differential method. This technique requires two identical capacitors, and their capacitance is measured using LCR meters. The capacitors are then connected in series and charged by a power supply. A spark gap is incorporated in the circuit for resonant discharge of the capacitors, which occurs when the voltage across the spark gap exceeds a predefined test voltage. A Current Transformer (CT) has been used for current measurement. The first and second peak values of the current are measured on oscilloscope, and the resonant frequency is calculated based on the time between these peaks.

Once the resonant frequency is determined, the total series resistance (Rt) and total series inductance (Lt) of the circuit are calculated using Equations (1) and (2) respectively. Next, one of the capacitors is shorted within the same setup, and the single capacitor is charged and then discharged resonantly. The frequency in this case is also measured, and the series resistance (R1) and inductance (L1) are calculated. These values of R1 and L1 are then subtracted from Rt and Lt respectively to determine the ESL and ESR of the removed capacitor.

$$L = \frac{(t_2 - t_1)^2}{4\pi^2 C} \tag{1}$$

$$R = \frac{2L \ln \frac{I_1}{I_2}}{t_2 - t_1} \tag{2}$$

Where t_1 and t_2 are the time at which first peak and second peak of current occurs, I_1 and I_2 are the values of current at first peak and second peak, C is the value of capacitance in the circuit.

The differential method is widely used for measuring ESL, and the error percentage can be calculated (1). However, the error in measuring ESR is not well understood. To address this issue and improve the measurement accuracy, simulations were performed using an ideal capacitor with series inductance and resistance.

The ESL and ESR values were measured using the above differential method. The circuit used for simulation incorporated the arc resistance of the spark gap, external inductance, external resistance, and switch turn-on time.

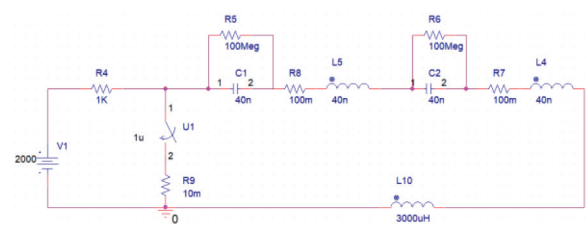

Figure 1. Simulation circuit with both capacitors connected.

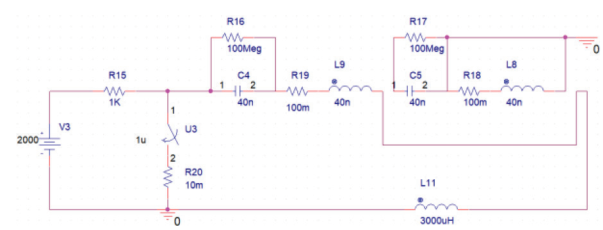

Figure 2. Simulation circuit with one capacitor shorted.

It was observed that varying the switch turn-on time introduced some errors in the ESR measurement. To mitigate this error and make the ESR measurement independent of the switch turn-on time, modifications were made to the circuit. An improved method was proposed, which involved incorporating a series of external inductances for more accurate ESR measurement. One advantage of using an external inductor is that it lowers the resonant frequency, reducing measurement errors. The turn-on time of the series switch also influenced the frequency of resonant discharge, thereby affecting the calculation of ESR. To eliminate the effect of the turn-on time, an external inductance was employed.

Simulations were conducted on ideal capacitors with ESL and ESR, including an external inductance of 3000 nH, to validate the proposed method. Two capacitors were connected in series as depicted in Figure 1, and the current was measured. The total inductance and total resistance were evaluated. Subsequently, as shown in Figure 2, one capacitor was shorted, and the evaluation of inductance and resistance was repeated for the single capacitor. The ESL and ESR values of the shorted capacitor were then calculated by taking the difference between the inductances and resistances.

In Figure 1 and Figure 2, the following variables were used: applied voltage V1, capacitance of capacitor 1 (C1), capacitance of capacitor 2 (C2), ESL of capacitor 1 (L5), ESL of capacitor 2 (L4), ESR of capacitor 1 (R8), ESR of capacitor 2 (R7), external inductance (L6), and arc resistance (R9). These components were incorporated into the circuit to simulate and evaluate the proposed method.

Table 1. ESL and ESR without external inductance

Applied Voltage	Switch Turn-on Time (ns)	Actual ESL of Both Capacitors (nH)	Actual ESR Both Capacitors (mOhm)	Additional Inductance in Series (nH)	ESR Calculated (mOhm)	Error in ESR (%)	ESL Calculated (nH)	Error in ESL (%)
2000V	10	50	20	0	19.965	**-0.171**	49.972	-.055
2000V	50	50	20	0	19.728	**-1.357**	49.619	-.760
2000V	100	50	20	0	19.966	**-0.166**	49.961	-.077
2000V	200	50	20	0	19.998	**-0.007**	49.961	-.076
2000V	300	50	20	0	20.669	**3.348**	50.677	1.354
2000V	400	50	20	0	21.592	**7.964**	50.314	0.628
2000V	500	50	20	0	24.193	**20.969**	50.672	1.345
2000V	600	50	20	0	28.440	**42.203**	51.028	2.056
2000V	700	50	20	0	34.274	**71.374**	51.382	2.765
2000V	800	50	20	0	42.559	**112.799**	52.476	4.952
2000V	900	50	20	0	51.341	**156.708**	52.122	4.244
2000V	1000	50	20	0	63.381	**216.905**	53.589	7.177

Table 2. ESL and ESR with 3000nH inductance in series

Applied Voltage	Switch Turn-on Time(ns)	Actual ESL of Both Capacitors (nH)	Actual ESR Both Capacitors (mOhm)	Additional Inductance in Series (nH)	ESR Calculated (mOhm)	Error in ESR (%)	ESL Calculated (nH)	Error in ESL (%)
2000V	10	50	20	3000n	20.007	**0.038**	51.007	2.01
2000V	50	50	20	3000n	20.012	**0.062**	51.007	2.01
2000V	100	50	20	3000n	19.990	**-0.048**	49.824	-0.35
2000V	200	50	20	3000n	20.020	**0.101**	51.007	2.01
2000V	300	50	20	3000n	20.039	**0.196**	53.784	7.56
2000V	400	50	20	3000n	20.057	**0.288**	53.786	7.56
2000V	500	50	20	3000n	20.006	**0.034**	53.799	7.56
2000V	600	50	20	3000n	19.958	**-0.209**	47.047	-5.90
2000V	700	50	20	3000n	19.926	**-0.366**	47.047	-5.90
2000V	800	50	20	3000n	20.031	**0.158**	53.388	6.77
2000V	900	50	20	3000n	19.978	**-0.106**	49.428	-1.14
2000V	1000	50	20	3000n	20.012	**0.060**	46.651	-6.69

In Table 1, the ESR values were calculated without connecting any external inductance, while Table 2 shows the ESR values calculated with an external inductance of 3000 nH in series with the discharging switch. The maximum error in ESR calculation without the external inductance was found to be less than 216% when the switch turn-on time varied from 10ns to 1000ns. However, with the inclusion of the external inductance of 3000 nH, the maximum error was reduced to less than 0.5% even when the switch turn-on time varied in the same range. To measure the ESR, a setup was created as shown in Figure 3 and Figure 4. Figure 3 illustrates the setup with both capacitors connected in series, while Figure 4 demonstrates the setup with one capacitor shorted. It is crucial that when shorting one capacitor, the shorting link should not introduce additional inductance and resistance. The resonant frequency could be affected, leading to potential errors. To avoid this, a wide copper foil with very low inductance and resistance was used to short the capacitor. Using this setup, the ESL and ESR of the newly developed capacitors were measured. The ESR of the newly developed capacitor was found to be 120 mOhm. Additionally, it was observed that the measurement repeatability improved when an external inductance was added to the circuit. The waveforms during measurements are shown in Figures 5 and 6.

Figure 3. Setup for ESR measurement with both capacitor.

Figure 4. Setup for ESR measurement with one capacitor shorted.

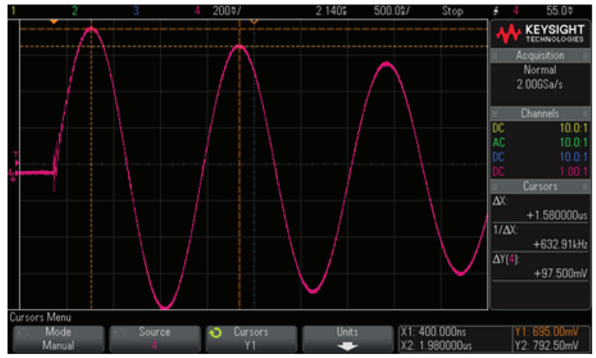

Figure 5. Current waveform with both the test capacitors in series.

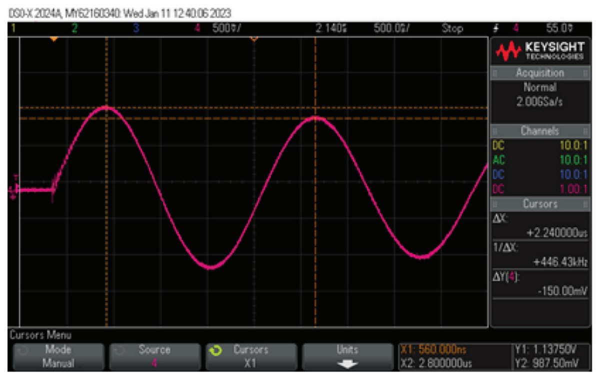

Figure 6. Current waveform with single test capacitor.

3. Conclusion

This paper focuses on the measurement techniques for assessing the performance of Pulse Forming Network (PFN) capacitors used in klystron-based microwave systems. The proposed measurement technique for ESR measurement involves using a differential method with two identical capacitors connected in series and an external inductance in series. To validate the proposed method, simulations were conducted using ideal capacitors with known ESL and ESR values. The simulations considered the impact of external factors such as arc resistance, switch turn-on time, and an added external inductance. The results demonstrate the effectiveness of the proposed method in accurately measuring ESL and ESR, with minimal error with respect to switch turn-on time. Furthermore, a practical setup was implemented to measure the ESL and ESR of newly developed capacitors with improved designs. The measurements revealed an ESR value of 100 mOhm for the new capacitors, highlighting their improved performance. The repeatability of the measurements was enhanced when an external inductance was incorporated into the circuit.

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