LOSS ESTIMATION OF CAPACITOR IN HIGH REP-RATE PULSED POWER SYSTEM

Chaofeng Huang, Paul Melcher, George Ferguson and Richard Ness
Cymer, Inc. 17075 Thornmint Court
San Diego, CA 92127 USA

Abstract

Capacitor loss in pulsed power systems has become an important issue for thermal management, especially when the operating rep-rate and energy per pulse are getting higher and higher. It is practical to analyze the loss of a capacitor using a capacitor series equivalent circuit model in this pulsed power application. The capacitor loss is directly related to the equivalent series resistance (ESR) of the capacitor. In the paper, the formula to estimate the capacitor loss is presented. It is proportional to the energy per pulse, rep-rate, and capacitor dissipation factor (tanδ) at the certain energy transfer frequency of the circuit. The charging and discharging frequencies of the capacitor might be different. Both of them will produce losses, and contribute to the total capacitor loss. The analysis of a capacitor bank with capacitors in parallel or in series is presented as well.

Also in this work, the parameters of different types of capacitors were measured, including film capacitors and high voltage ceramic capacitors, using a Agilent 4285A Precision LCR Meter up to 13MHz. The influence of temperature on capacitance and dissipation factor was investigated by sinking the capacitor in oil under controlled temperatures. The results are very helpful to estimate the losses of capacitors in Cymer's laser pulsed power systems, and to provide design guidelines to the next generation of 6 kHz laser power systems.

I. INTRODUCTION

In Cymer's laser pulsed power system, a high voltage IGBT is used as the switching device in the resonant energy transfer circuit from C0 to C1, and magnetic switches are used for resonant circuits from C1 to Cp-1 and Cp-1 to Cp. The simplified schematic diagram of the Solid-State Pulsed Power Module (SSPPM) is shown in Figure 1.

C0 is charged by a resonant charger, and discharged into C1 by closing the IGBT switch. Then C1 discharges through a magnetic switch LS1 and a high voltage pulse transformer to Cp-1. Cp-1 discharges through magnetic switch LS2 to Cp and the laser chamber to generate laser light. Film capacitors are used for C0 and C1, and high voltage ceramic capacitors are used for Cp-1 and Cp.

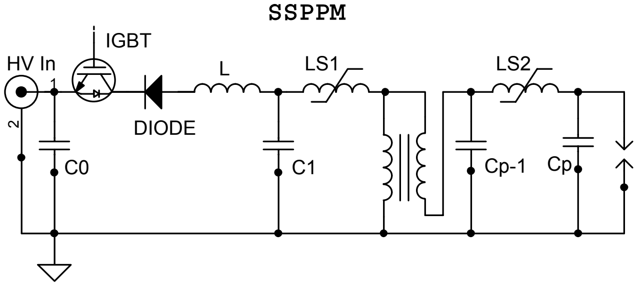

Figure 1. Simplified schematic diagram of SSPPM

The losses of the IGBT, series Diode and magnetic switch were studied before [1][2]. The analysis and test results presented in this paper are on the losses of capacitors as part of the SSPPM efficiency improvement and thermal management effort.

II. CAPACITOR MODELS

There are many different capacitor models. The two element and three element models are discussed here.

A. Two Element Series Model

The impedance vectors and capacitor series equivalent circuit model are shown in Figure 2.

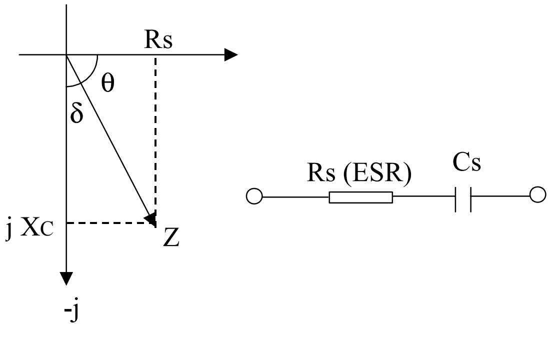

Figure 2. Capacitor two element series model

Z : impedance; θ: phase angle
δ: the dielectric loss angle (complementary angle to θ)
Cs : equivalent series capacitance
Rs : equivalent series resistance (ESR)
D : capacitor dissipation factor at energy transfer frequency (tanδ)

The relationships of parameters are as follow.

$$Z = R_s - j\,X_C\ ;\ X_C = \frac{1}{\omega C_S} = \frac{T}{2\pi\, C_s}$$

$$D = \tan\delta = \frac{R_S}{X_C} = R_S \bullet \omega C_S$$

$$R_s = D \bullet X_C = \frac{D}{\omega C_S} = \frac{T \bullet \tan\delta}{2\pi\, C_S}$$

B. Three Element Series Model

Figure 3 is a three element series circuit model by taking into account the capacitor series equivalent inductance (Ls).

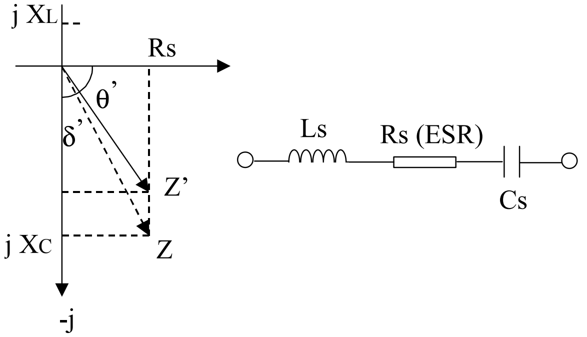

Figure 3. Capacitor three element series model

Rs is the most important parameter to consider for capacitor loss estimation. For the pulsed power system, the capacitor is usually used well below the self-resonant frequency $f = 1/\left(2\pi\sqrt{L_s C_s}\right)$. Ls could be neglected here for our engineering application.

III. CAPACITOR LOSS IN PULSED POWER CONDITION

Considering the resonant energy transfer circuit from C0 to C1 in Figure 1, the losses of C0 and C1 are estimated as follows. C0 is charged to *Vm*, and discharged to C1 through inductor L by closing the IGBT (and assuming initial voltage on C1 is zero). The resistance of C0, C1 and IGBT and Diode are considered much smaller than the impedance of the charging inductor L and lumped capacitance.

The current would be a half sinusoidal waveform with period of *T* and peak current of *Im* as shown in Figure 4.

$$I(t) = I_m \bullet Sin(\omega t)$$

$$\omega = \frac{2\pi}{T} = \frac{1}{\sqrt{L \bullet C_T}}$$

$$C_T = \frac{C_0 \bullet C_1}{C_0 + C_1}$$

$$I_m = V_m \bullet \sqrt{\frac{C_T}{L}} = \frac{2\pi \bullet V_m \bullet C_T}{T}$$

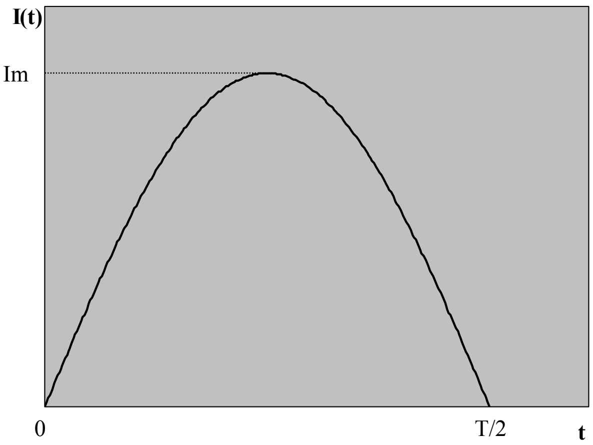

Figure 4. Current waveform from C0 to C1

Final voltage on C0 and C1 at end of charge T/2:

$$V_{C0} = V_m \bullet \left(1 - \frac{2C_1}{C_0 + C_1}\right)\ ;\ \ V_{C1} = V_m \bullet \frac{2C_0}{C_0 + C_1}$$

Transferred energy per pulse:

$$E = \frac{1}{2} \bullet C_1 \bullet V_{C1}{}^2 = 2 \bullet V_m{}^2 \bullet \frac{C_0{}^2 \bullet C_1}{(C_0 + C_1)^2} = \frac{2 \bullet V_m{}^2 \bullet C_T{}^2}{C_1}$$

The equivalent series resistance of C0 and C1:

$$R_{S0} = \frac{T \bullet \tan\delta_0}{2\pi\, C_0}\ ;\ \ R_{S1} = \frac{T \bullet \tan\delta_1}{2\pi\, C_1}$$

Energy loss on C0 per pulse:

$$\Delta E_0 = \int_0^{T/2} R_{S0} \bullet I(t)^2 \bullet dt = R_{S0} \bullet I_m{}^2 \bullet \int_0^{T/2} Sin^2(\omega t) \bullet dt$$

$$= \frac{R_{S0} \bullet I_m{}^2 \bullet T}{4} = \frac{\pi}{2} \bullet \tan\delta_0 \bullet \frac{V_m{}^2 \bullet C_T{}^2}{C_0}$$

$$= \frac{\pi}{4} \bullet \tan\delta_0 \bullet \frac{C_1}{C_0} \bullet E$$

Energy loss on C1 per pulse:

$$\Delta E_1 = \int_0^{T/2} R_{S1} \bullet I(t)^2 \bullet dt = \frac{\pi}{2} \bullet \tan\delta_1 \bullet \frac{V_m{}^2 \bullet C_T{}^2}{C_1}$$

$$= \frac{\pi}{4} \bullet \tan\delta_1 \bullet E$$

C0 discharging loss (power dissipation) at pulsed rep-rate condition:

$$C_0 Loss = \frac{\pi}{4} \bullet \tan\delta_0 \bullet \frac{C_1}{C_0} \bullet E \bullet (rep - rate) \quad \text{-----(1)}$$

C1 charging loss (power dissipation) at pulsed rep-rate condition:

$$C_1 Loss = \frac{\pi}{4} \bullet \tan\delta_1 \bullet E \bullet (rep - rate) \quad \text{----------(2)}$$

One can see from formula (1) and (2) that the capacitor loss at pulsed power condition is proportional to the capacitor dissipation factor, transferred energy and the pulse rep-rate. Also the loss formulas are different between discharging and charging capacitors if their capacitances are different.

The formulas are also applicable to the C1 / Cp-1, and Cp-1 / Cp energy transfer loops.

IV. CAPACITOR BANK

Usually, the capacitor bank used for C0, C1, Cp-1, or Cp consists of the same individual capacitors in a parallel and/or series array.

A. Capacitors in Parallel

Figure 5 shows a number of n capacitors in parallel and the equivalent circuit.

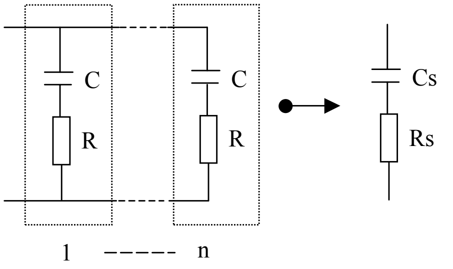

Figure 5. Capacitors in parallel

$$C_S = n \bullet C\,; \quad R_S = R/n$$
$$\tan\delta_S = R_S \bullet \omega C_S = R \bullet \omega C = \tan\delta$$

One can see that the dissipation factor of the capacitor bank with parallel capacitors equals to that of the single capacitor.

B. Capacitors in Series

Figure 6 shows a number of n capacitors in series and the equivalent circuit.

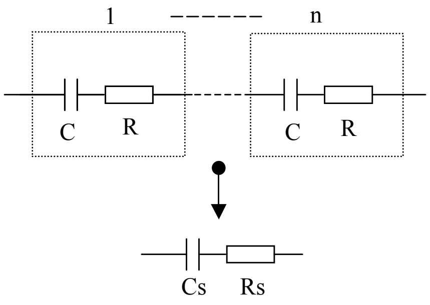

Figure 6. Capacitors in series

$$C_S = C/n\,; \quad R_S = n \bullet R$$
$$\tan\delta_S = R_S \bullet \omega C_S = R \bullet \omega C = \tan\delta$$

One can see that the dissipation factor of the capacitor bank with series capacitors equals to that of the single capacitor.

If a capacitor bank consists of same capacitors in parallel or series array, the dissipation factor of a single capacitor can be used to calculate the whole capacitor bank loss by formulas (1) or (2).

V. CAPACITOR MEASUREMENT

An Agilent 4285A Precision LCR Meter was used to measure the parameters of polypropylene film capacitor and high voltage ceramic capacitor samples.

A. Film capacitor 0.047uF, 2000VDC

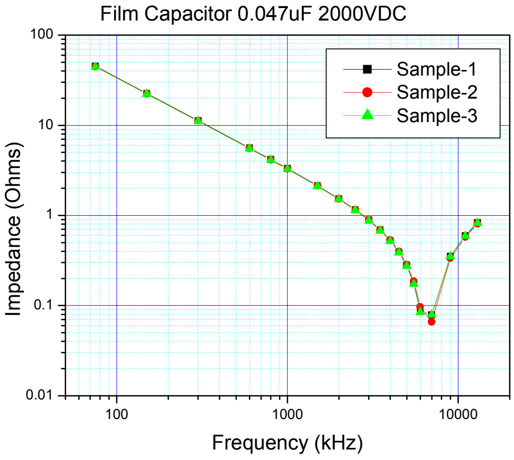

Figure 7. The impedance changing with frequency

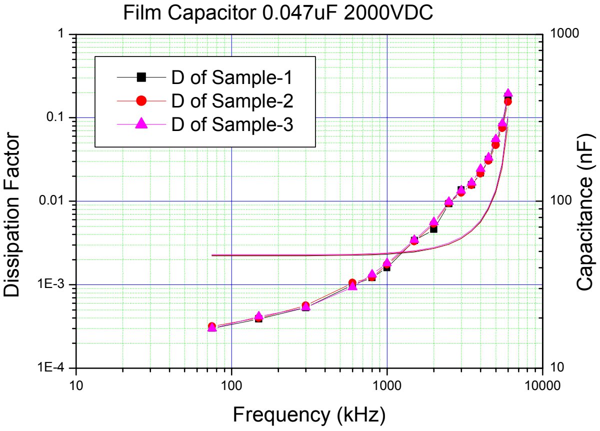

Figure 8. Capacitance and dissipation factor vs. frequency

Figure 7 shows the measured impedance changing with signal frequency. The capacitive reactance dominates at the low frequency range (less than 7 MHz) and the impedance decreases with increasing frequency. At the high frequency range (greater than 7 MHz), the inductive reactance dominates. The self-resonant frequency is about 7 MHz.

Figure 8 shows the measured capacitance and dissipation factor changing with frequency.

B. *High voltage ceramic capacitor 390pF, 50kV*

Figure 9 shows the measured impedance changing with frequency up to 13MHz, which is the limit of the Test Fixture. The ceramic capacitor self-resonant frequency is beyond 13MHz.

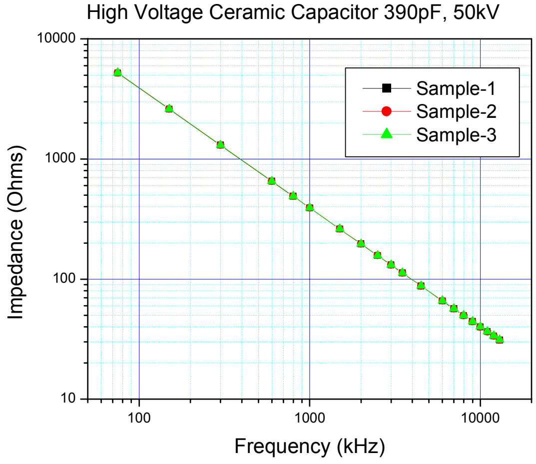

Figure 9. The impedance changing with frequency

Figure 10 shows the measured capacitance and dissipation factor changing with frequency.

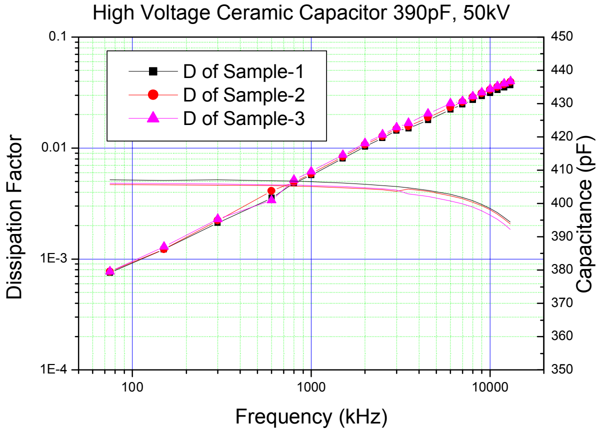

Figure 10. Capacitance and dissipation factor vs. frequency

C. *Temperature influence on capacitors*

The temperature influence on capacitance was measured by sinking the capacitors in oil under controlled temperature. Figure 11 shows the capacitance changing with temperatures at 1MHz. One can see that the temperature coefficient of the ceramic capacitor (4220PPM) is much larger than the film capacitor (365PPM).

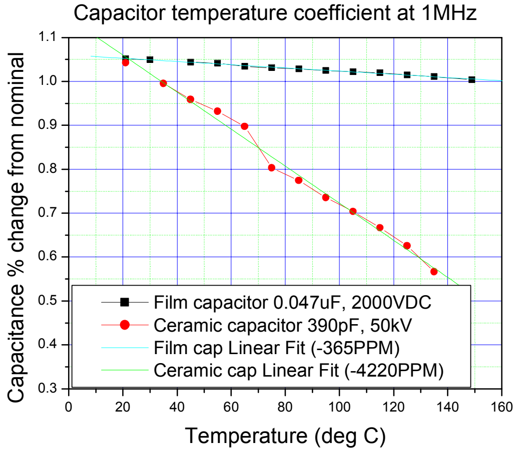

Figure 11. Capacitance change vs. temperature at 1 MHz

D. *One example of capacitor Cp-1 loss estimation*

Assuming C1=Cp-1=Cp, Cp-1 consists of 20 pieces of 390pF ceramic capacitors, energy transfer on Cp-1 is 5.0J/pulse, rep-rate is 6 kHz, Cp-1 charging time is 333ns, (D = 8.0E-3 at 1.5 MHz from Figure 10), discharge time is 71.4 ns (D=0.025 at 7MHz from Figure 10).

$$C_{p-1} Total\ Loss = C_{p-1} Ch\arg e\ Loss + C_{p-1} Disch\arg e\ Loss$$

$$= \frac{\pi}{4} \times (8.0E-3+0.025) \times 5.0 \times 6000 = 777.5\ \ (W)$$

VI. SUMMARY

The capacitor loss in pulsed power rep-rate condition is analyzed in the paper. And also the parameters of capacitors were measured. The following conclusions are observed:

- The capacitor charging or discharging loss is proportional to the dissipation factor, energy transfer per pulse, and the pulse rep-rate.
- The dissipation factor of a capacitor bank consisting of same capacitors in parallel or series array is the same as an individual capacitor.
- The dissipation factors of the film capacitor and ceramic capacitors are increasing with signal frequency. Measured capacitance of the film capacitor increases with frequency; capacitance of the ceramic capacitor decreases with frequency.

VII. REFERENCES

[1] Chaofeng Huang, Paul Melcher, George Ferguson and Richard Ness, “IGBT and Diode Loss Measurements in Pulsed Power Operating Conditions”, 2004 Power Modulator Conference, San Francisco, May 23-26, 2004.

[2] Kenneth McDonald, Randy Curry, Renuka Narsetti, Richard Ness, Paul Melcher, and Chaofeng Huang, “Evaluation of Magnetic Materials and Insulation Systems for Repetition-Rate Pulse Compression Applications”, 14th IEEE International Pulsed Power Conference, Dallas, Texas, USA, June 15-18, 2003.