PERFORMANCE OF HIGH POWER CAPACITORS FOR PULSED PLASMA THRUSTER APPLICATIONS

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Abstract

Pulsed plasma thrusters (PPTs) are electric propulsion devices in which the propellant is accelerated electromagnetically. Pulse duration is typically on the order of 1-10 μs. Recent interest in small satellites has sparked renewed interest in PPTs. Improved pulsed plasma accelerators are undergoing development for use as long-life thrusters for propulsion of spacecraft on interplanetary missions and for maneuvering of small spacecraft in orbit around the earth. PPTs are simple, low mass, and require only low input power (less 200W). The PPT is a high precision propulsion and accurate attitude control system. One of several key areas which need to be improved is to increase the average thruster-to-weight ratio. One of reasons causing low thruster-to-weight ratio is propellant inefficiency resulting from the ejection of propellant material (Teflon) in large particulate form. Reportedly, about 30% of the total propellant mass is ejected in large particulate form with sizes ranging from 100 μm to about 1 μm. One of the ways to improve efficiency is to increase pulsed power level, which can result in an increase of the plasma temperature, and, therefore improve the efficiency of utilization of propellant material. However, further increasing pulsed power level requires the energy storage unit, i.e. capacitors, that have much higher energy density and power density than those currently in use. These new capacitors must also be able to deliver their stored energy in a much shorter time period. In other words, to improve efficiency, the capacitor needs have higher working voltage, higher capacitance, much lower ESR and inductance and, of course, long cycle lifetime. These requirements are beyond the limits of most currently available commercial capacitors. This paper will present the results of performance tests on two different types of advanced capacitors provided by leading capacitor companies. The levels of deliverable power and energy density of the capacitors will be discussed.

I Introduction

Pulsed plasma thrusters (PPTs) are electric propulsion devices in which the propellant is accelerated electromagnetically. Using advanced solid-state electronic circuits, the pulse rate increases significantly and the pulse plasma duration is typically on the order of microseconds.[1,2] Recent interest in small satellites has sparked renewed interest in PPTs. Improved pulsed plasma accelerators are undergoing development for use as long-life thrusters for propulsion of spacecraft on interplanetary missions and for maneuvering of small spacecraft in the orbit around the earth. PPTs are simple, low mass, and require only low input power (less 200W).[3,4] The PPT is a high precision propulsion and accurate attitude control system. One of several key areas which need to be improved, is to increase the average thruster-to-weight ratio. One reason causing low thruster-to-weight ratio is propellant inefficiency resulting from the ejection of propellant material (Teflon) in large particulate form. Reportedly, about 30% of the total propellant mass is ejected in the large particulate form with sizes ranging from 100 μm to about 1 μm.[5] One way to improve efficiency is to increase pulsed power level, which can increase the plasma temperature, and therefore improve the efficiency of utilization of propellant material. However, further increasing pulsed power level requires the energy storage unit, i.e. capacitors, that have much higher energy density and power density than those currently used. These new capacitors must also be able to deliver their stored energy in a much shorter period. In other words, to improve efficiency, the capacitor needs have higher working voltage, higher capacitance, much lower ESR and inductance and, of course, long cycle lifetime.

II Background

The PPT consists of four major parts; the mechanical thruster, energy storage unit (ESU), electronics, and discharge initiation component. The key component in ESU operation is the high efficiency capacitor, which stores and releases energy to vaporize Teflon and thus generate thrust. In the past, oil-filled capacitors have dominated the energy storage system for pulsed plasma thruster applications. Although these capacitors possess extremely high charge-discharge cycle ability at very high voltage, they suffer from low energy densities and poor energy to volume ratios. Hermetic sealing and packaging are subject to internal breakdowns which can lead to complete system failure.

A capacitor, as practical device, can be represented as an equivalent circuit shown in figure 1. The model comprises four ideal circuit elements: a capacitor C_1, a series resistor Rs, a parallel resistor Rp, and a series inductor L_1. Rs is also called ESR and contributes to energy loss during capacitor charging and discharging. Rp simulates energy loss due to capacitor leakage current. L_1 is also a major contributor for energy loss when the capacitor is operated at a high frequency of charging/discharging (~1000 kHz). The energy loss in a capacitor is often expressed by a dissipation factor (D.F.), which is

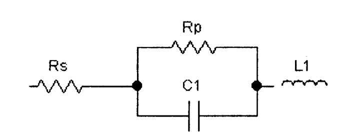


Figure 1 An equivalent circuit a of capacitor.

$$D.F. = \tan\delta \text{ , } \tan\theta = \tan(90^{o} - \delta) = \frac{Z'}{Z''} \quad (1)$$

where δ and θ are loss angle and phase angle, respectively, Z' is resistance, and Z" is total reactance. Z" is the sum of the reactance in the circuit, i.e. the capacitor C and the inductor L. Z" is equal to:

$$Z'' = \left|Z_L''\right| - \left|Z''_c\right| \quad (2)$$

A capacitor with a low D.F. will provide high efficiency energy storage for the PPT. Z_c'' and Z_L'' are functions of frequency, which can be expressed:

$$Z_C'' = \frac{1}{2\pi fC} \text{ and } Z_L'' = 2\pi fL \quad (3)$$

where C is capacitance, L is inductance, and f is frequency. In order to reduce D.F., Z''_L must be very small at the operating frequency. Therefore, a capacitor with low ESR, low L, and high Rp is highly desired for the PPT to have high power and high efficient energy storage.

III Capacitors

Two capacitors were used for this investigation; one is a metallized film capacitor (MF) and the other is a multilayer ceramic capacitor (MLC). MF has 45 μF capacitance and MLC has 100 μF. The power performance is the focal point of this investigation.

A Power Performance

Figure 2 shows the frequency response curves of both capacitors. At phase angle equal to zero, the frequency is the self-resonance frequency (f_R) of the capacitor. At frequencies below f_R, the device is capacitive (negative phase angle) and at higher frequencies, the device is inductive (positive phase angle). Capacitors are effective energy storage devices only below their self-resonance frequency. MLC has higher f_R (400 kHz) than the MF f_R (60 kHz). Keeping in mind, f_R is a function of capacitance and inductance of the capacitor, and can be described as:

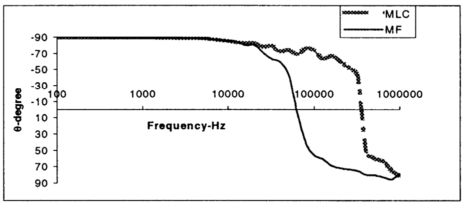


Figure 2 The phase angles of the capacitors are plotted against frequencies.

$$f_R = \frac{1}{2\pi(LC)^{1/2}} \quad (4)$$

The capacitor with a smaller capacitance should have higher f_R. Higher f_R is desired for PPT applications. It is obvious that MLC has an advantage over other types of capacitors. The MLC can be operated at very high frequencies (above 1 MHz) provided that the capacitance of the MLC is less than 45 μF. However, the MF also has its advantages, these include large surface areas and self-healing capability. As a result, over 2 kA current can be discharged through the capacitor without causing any damage in the capacitor. With continuing improvement of its mounting technology, the MF should be able to operate at frequency above 500 kHz.

With discharge rates below the capacitor f_R (which is reasonable because most of PPT is operated at a discharge rate around 100kHz) the inductor in Figure 1 can be eliminated without loss of accuracy because the inductance of the capacitor is very small compared to the capacitance. Thus, the simplest model of any capacitor is a series RC circuit. This model is comprised of two ideal elements and applies at frequencies below f_R when capacitor self-discharge is unimportant because R_p is very large for both MLC and MF. The energy stored in a series-RC circuit is

$$E = \frac{1}{2} C V_o{}^{1/2} \qquad (5)$$

where V_o is the working voltage of the capacitor. Stored energy in the voltage range $V_o/2$ to V_o is 0.75E. We assume that when the voltage drops to one half of the working voltage, the plasma will not be sustained.

The power delivered to a resistive load by a series RC circuit that is initially charged to its working voltage is

$$P_L = [4 P_{max} / (1+r)^2] e^{[-2\chi/(1+r)]} \qquad (6)$$

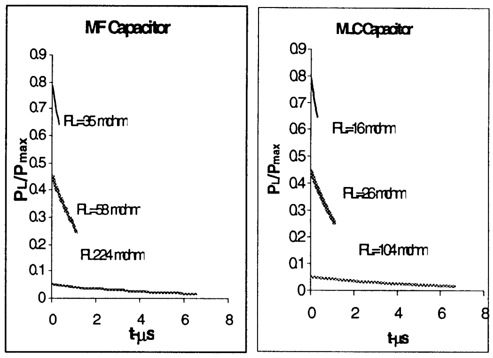
where:

$$P_{max} = \frac{V_o^2}{4 R_s}$$

$$\text{and } \chi = \frac{t}{R_s C} \quad r = \frac{R_L}{R_s} \qquad (7)$$

where t is capacitor discharge time, R_L is the resistance of the plasma, and P_{max} is the maximum power that can be delivered by the capacitor. When R_L is equal to R_s (a so-called matched load) the capacitor's voltage immediately drops from V_o to $V_o/2$ when the discharge begins. Thus, the delivered energy is zero for a lower voltage limit of $V_o/2$. This is because we assumed that the plasma would not be sustained when the voltage drops to $V_o/2$. The capacitor still can deliver energy but the voltage will be lower than $V_o/2$.

The power performance is strongly dependent upon the ratio of plasma resistance and capacitor's ESR. It is well known that the pulsed discharge plasma can quickly reach a steady state after being initiated.[6] The resistance of the steady state plasma is about several hundred mΩ based on the discharge voltage and current waveforms of the plasma in a PPT test. The measured ESRs of MF and MLC are 28 mΩ and 13 mΩ, respectively. Figure 3 plots the normalized power P_L/P_{max} of these two capacitors against discharge time, t, for three R_L/R_s ratios (r=1.25, 2, and 8, see equation 7). The plasma resistances (R_L) calculated based on R_L/R_s ratios using R_L=r x R_s are marked in figure 3. At the R_L/R_s ratio, the calculated plasma resistance is different between these two capacitors because they have different R_s (ESR). The end point of each line corresponds to the time needed to reach voltage $V_o/2$. From Equation (7), the maximum power for these capacitors is 35,714 kW for MF and 2,355 kW for MLC. Thus the initial power is about 79% for the plasma resistance at 1.25 times of the capacitor's ESR and only 5% for the plasma resistance at 8 times of the capacitor's ESR. That is, for plasma resistance of 35 mΩ, the MF can provide an initial power level at 28,214 kW. However, if the plasma resistance is



a b

Figure 3 Power versus discharge time for a series-RC circuit with plasma resistance. Power normalized by the maximum deliverable power of the capacitor.

224 mohm, MF can only provide an initial power level of 1,785 kW. It is the same principle for the MLC shown Figure 3 b.

The plots clearly demonstrate that an appropriate combination of capacitor's ESR and plasma resistance is a very important factor that can result in high deliverable power from the capacitor. For energy efficiency, the capacitor with small ESR should always give the higher energy efficiency. The smaller the ESR, the less energy is dissipated in the capacitor.

B. Energy Density

The another important factor in the ESU is energy density. The MF is able to deliver extremely high power, however, MLCs have a higher energy density than any other type of capacitor. They exhibit small packaging sizes, which surpass the conventional capacitor technology currently used in PPT applications. The specification of these capacitors is listed in table 1. Figure 4 shows the energy density as well as the specific energy of three capacitors for PPT application. OC stands for oil-filled capacitor which is currently used for PPTs. The higher energy density of the MLC comes from its small volume. This small volume is mitigated in small measure by its lower operating voltage.

Table 1 Capacitor Specification

	V(V)	C(μF)	W(g)	Vol.(cm^3)
OC	2000	39	1500	825
MF	2000	45	957	560
MLC	350	100	150	31

Just very recently, Lawrence Livermore laboratory announced new state of art MLC technology that increases the energy density of the MLC to 5000 mJ/cm^3. However, MF has the advantage in terms of specific energy. Both MF and MLC are very competitive technologies for PPT application because their high power capability and compact size and relatively light mass.

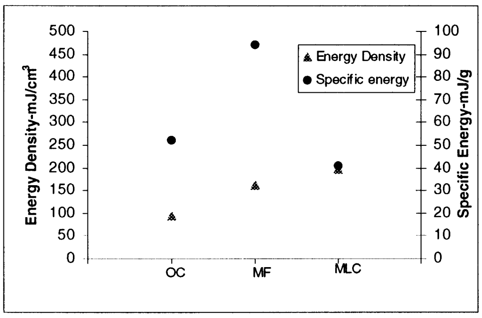


Figure 4 Energy density and specific energy of advanced capacitors.

Summary

MF and MLC capacitors have shown they are appropriate for PPT energy storage application. Both capacitors can be discharged at high rates around 100 kHz with good efficiency (low inductance) so as to deliver high power to initiate and sustain the plasma discharge. The combination of ESR and plasma resistance has a significant influence on the power delivery of the capacitors. The MF capacitor is able to deliver extremely high power, but MLC has the most energy density and lower inductance. Additionally, the MLC is also compatible with surface mount technology, which can be more easily integrated into electric circuits to achieve more compact electronics. This also reduces additional inductance caused by long terminal leads that other types of capacitors have. In contrast, MFs usually do not have this advantage; but they have a unique advantage, that is self-healing capability. As a result, MFs can be very reliable for high power applications.

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