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RECENT ADVANCES IN HIGH VOLTAGE, HIGH ENERGY CAPACITOR TECHNOLOGY

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Abstract

Capacitors continue to be major components of pulsed power systems, especially as energy storage and pulse discharge devices. On-going research and development at GA-ESI (formerly "Maxwell") in capacitor technology and dielectric materials has resulted in significant expansion in several dimensions of the film capacitor operating envelope. Examples of such advances include increased energy density, increased energy per unit, longer DC life at high energy density, lower temperature (cryogenic) operation, faster discharge capability, higher continuous working specific power, and higher reliability. Future improvements are expected in all of the above performance parameters as well as higher temperature operation.

I. BACKGROUND

Pulse power capacitors are generally high voltage, fast-discharge devices designed to have low inductance and low series resistance. Typically they are charged over a relatively long period of time and then discharged via a closing switch in microseconds or milliseconds. Such capacitors act as energy storage and power pulse compression devices. Figures of merit used in assessing such capacitors include energy density, inductance, peak current rating, and reliable lifetime.

Self-healing metallized electrode capacitors were first developed during the Second World War and have since largely displaced discrete foil capacitors in most DC and 50/60 Hz AC applications. This technology has been adapted and applied in an increasing number of pulse power applications over the last three decades. Recent advances have significantly expanded the operating parameter envelope for self-healing capacitors for pulse power applications.

This paper will focus on the results of GA-ESI's efforts to expand the operating envelope of self-healing capacitors to fulfill the needs of an ever-broader range of pulse power applications. In addition, the parameters in which non-self-healing, foil electrode capacitors outperform self-healing capacitors will be highlighted. Future development of metallized capacitor technology will largely be focused on these parameters.

II. THE CAPACITOR OPERATING ENVELOPE

A. Energy Density or Specific Energy

The specific energy, D, in J/cc or MJ/m^3 of a capacitor may be calculated using

$$D = 4.44 \times 10^{-6}\ PF\ K\ E^2 \qquad (1)$$

where PF is the Packing Factor (fraction of the total volume which is storing energy), K is the relative permittivity of the dielectric ($\varepsilon/\varepsilon_0$), and E is the electric field in V/µm. The packing factor of self-healing capacitors is highly dependent on voltage and peak current requirements. In high energy density millisecond discharge capacitors operating at about 5 kV, the packing factor can be as high as 70-80%. In microsecond discharge capacitors the packing factor can be less than 50%. The relative permittivity of available polymer films ranges from 2 to 11. Electric fields are limited by the breakdown strength of the polymer film, which is typically 500-800 V/µm for capacitor grade films. Self-healing capacitors designed for short lifetimes (e.g. 1000 cycles) may be operated as high as about 75% of the breakdown strength, whereas long-lived components or those requiring high stability or extreme reliability are designed to be operated at significantly reduced electric fields.

Increased energy density has largely been achieved by increasing the electric field in the dielectric. To allow this, the polymer film was improved via higher resin purity, the metallized electrodes were improved to reduce the damage in each self-healing or "clearing" event, and capacitor manufacturing processes were optimized to insure complete liquid impregnation between layers of film. An on-going process of testing and failure analysis, with feedback to the various manufacturing operations, has resulted in continuous gains in performance.

In 2004, GA-ESI supplied 2.3 J/cc capacitors for an experimental electrothermal ignition system for a vehicle-mounted gun. In 2005, we demonstrated a 2.68 J/cc capacitor as part of our development program. Earlier this year, a 50-kJ, 3.0-J/cc capacitor with lifetime in

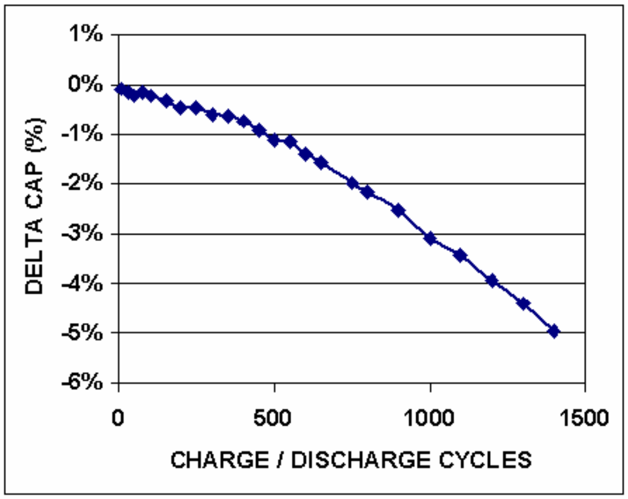

Figure 1. Life test data on 3 J/cc capacitor, showing capacitance loss versus number of cycles.

Figure 2. A 3.0 J/cc, 50-kJ capacitor.

excess of 1000 charge/discharge cycles was life tested in our facility. The change in capacitance with number of charge/discharge cycles is shown in Figure 1. The product itself is shown in Figure 2. These high energy-density capacitors were all designed for millisecond discharge pulse applications.

B. Energy per Unit

In 2005, GA-ESI built and tested a single capacitor which delivered over 290 kJ of energy in a few milliseconds. This unit was life tested to over 1000 cycles at an energy density of over 2.6 J/cc. The method of construction of these capacitors using assemblies of small winding elements is amenable to scaling to even larger energy storage per unit if needed. Self-healing eliminates the need to derate the operating voltage as a function of area under stress, as is required for non-self-healing electrostatic capacitors, such as film-foil designs. Large capacitors generally have improved packing factor (fraction of the total volume actually storing energy) and therefore slightly higher energy density than small capacitors, all else being equal.

C. Pulse Life

The life of high energy density pulse capacitors at a given energy density or physical size can also be increased as the result of the most recent advances. For example, the life of a 1.0-J/cc capacitor can now be increased from about 10,000 cycles to about 120,000 cycles. Figure 3 shows the lifetime versus electric field curves for both Type CMF capacitors and the new technology designs.

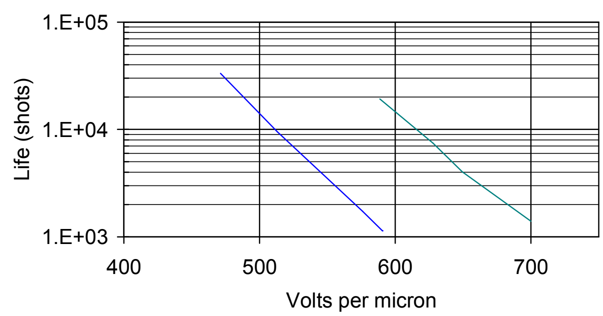

Figure 3. Pulse life of the latest generation of self-healing capacitors compared to the previous technology, Type CMF, as a function of electric field.

D. DC Life at High Energy Density

Some pulse power applications require that the capacitive energy store remain fully charged for long periods of time until discharge is triggered by an unpredictable external event. In such cases, long dc life of the capacitor is required. Initial experiments at GA-ESI showed that the dc life of high energy density capacitors was often measured in hours or tens of hours, rather than the thousands of hours desired. To improve this aspect of performance, GA-ESI investigated the degradation mechanisms in these capacitors, such as ionic conduction, and addressed shortcomings in material purity, sources of contamination in manufacturing, etc. Designs were also optimized for long DC life through selection of polymer film, film thickness, metallization alloy, and liquid impregnant. As the result of these efforts, GA-ESI has demonstrated a 1.3 J/cc capacitor with over 3000 hours DC life at room temperature that is capable of delivering 12.5-kJ of energy to a resistive load in a few microseconds. The capacitance change with hours on charge is shown in Figure 4.

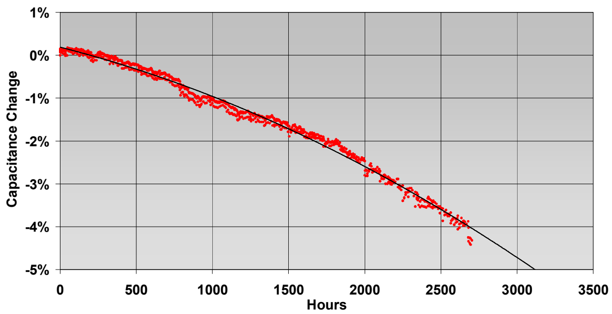

Figure 4. DC Life test data on a 1.3 J/cc capacitor.

E. Cryogenic Operation

General Atomics tested GA-ESI commercial off the shelf (COTS) capacitors in liquid nitrogen (77 ºK) under both pulse discharge and steady-state dc voltage conditions. It was found that lifetime was increased by at least a factor of seven (7) under both types of duty compared to room temperature performance. The life tests under cryogenic conditions were suspended before any failures occurred.

F. Discharge rate

One of the primary limits of metallized electrode, self-healing capacitors is in their discharge rate, often tabulated as Volts per microsecond (V/µsec) ratings by capacitor suppliers. Fundamentally, a given type of capacitor has a certain current density capability at the termination of the metallized electrode or in the metallization itself. This current density can be described in terms of Amps per centimeter (A/cm) of winding length. This parameter, as well as dielectric width, film thickness, and permittivity (e.g. capacitance per centimeter) determines the V/µsec rating of a given type of capacitor.

Because of different metallization thicknesses, alloys, and termination processes used, different manufacturers may achieve different current density levels in similar products.

To date, GA-ESI has achieved over 200 V/µsec at 10kV in high energy density microsecond discharge self-healing capacitors. Higher values can be achieved at lower energy densities by optimizing the electrodes for current-carrying rather than self-healing. In contrast, the limitation on discharge rate in foil capacitors is due to parasitic inductance and not current density. Much higher discharge rates have been achieved in GA-ESI's foil electrode capacitors, on the order of 0.1 MV/ µsec in large metal case Marx generator capacitors storing over 10 kJ per unit and about 0.2 MV/µsec in special low inductance plastic-case capacitors storing about 100 Joules per unit, such as those designed for Linear Transformer Drivers (LTDs). These latter capacitors, shown in Figure 5, have self resonant frequencies as high as 7 MHz and are rated at 100 kV.

Figure 5. Examples of 100 kV capacitors for LTDs.

Figure 6 compares several GA-ESI capacitors, both foil electrode and metallized electrode designs, to representative ultracapacitors and lithium ion pulse discharge batteries.

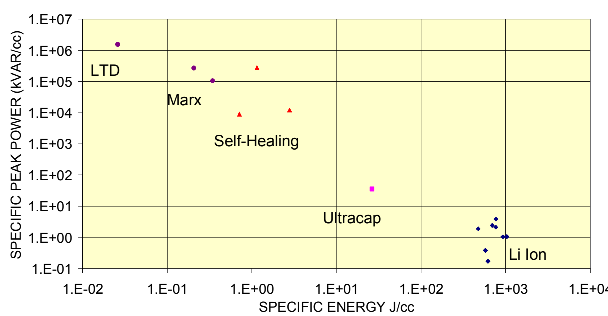

Figure 6. Specific Peak Power vs Specific Energy for some GA-ESI capacitors and other energy storage devices [1].

G. Maximum Voltage Ratings

Closely related to the discharge rate discussed in the preceding section, the maximum voltage capability of self-healing capacitors is limited principally by the current density limitation in the termination of the metallized electrode. For a given type of capacitor and value of stored energy, the total length of the winding edge carrying the terminal current is proportional to the capacitance and inversely proportional to the square of the voltage. As the voltage is increased by connecting winding elements in series, the current rating therefore decreases, as illustrated in Figure 7.

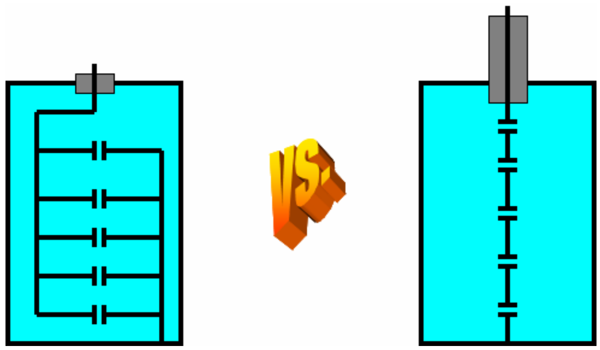

Figure 7. Comparison of two capacitors built with the same winding elements, one all in parallel and the other all in series, to illustrate the relationship between current density limitations and maximum voltage capability.

For microsecond discharge rates, the voltage is presently limited to about 12 kV, whereas for millisecond discharges, the maximum voltage is about 30 kV. Longer discharge times and lower peak currents permit higher voltages, and self-healing pulse capacitors up to 60 kV have been supplied. For low current DC filter applications, self-healing capacitors rated as high as 100 kV have been supplied by GA-ESI. (It should be noted that the capacitance on such high voltage capacitors should be monitored to detect degradation that could lead to an internal flashover.)

For comparison, foil electrode capacitors rated up to 2.2 MV and capable of microsecond discharge have been supplied by GA-ESI.

H. Specific Power

Another limitation of metallized electrode capacitors compared to foil electrode capacitors is their inability to carry high RMS currents. Metallized electrodes have much higher ohmic resistance than discrete metal foils, since they are about two orders of magnitude thinner. In addition, metallization does not provide the same excellent thermal conduction from the interior to the exterior of a winding that foil electrodes do, so that there is a much larger thermal gradient in metallized capacitors when dissipating the same amount of power per unit volume.

The capacitor designer can address this limitation by using relatively thick metallized electrodes and relatively narrow film widths when higher RMS current capability is necessary. These thicker electrodes are often segmented and interconnected with fusible links to achieve reliable self-healing. Hybrid designs that combine discrete foil electrodes with metallized electrodes are also utilized.

GA-ESI has achieved 0.10 kVAR/cc specific power in certain of its long-life self-healing capacitors. Manufacturers utilizing foil electrodes have achieved specific power ratings of 3.3 kVAR/cc in specialized conduction-cooled designs [1]. High specific power is also achieved in water-cooled capacitors.

I. Reliability

Typical acceptance test failure rates for large high energy density (0.6 J/cc) paper-foil capacitors have been 5 to 10%. Typical failure modes are bulk dielectric breakdown and foil edge breakdown, resulting in short-circuit failure. In some cases, relatively high failure rates have also been experienced in the field.

Metallized capacitors generally do not fail short-circuit, but instead tend to lose capacitance and/or increase in series resistance. Increase in series resistance is generally a current-induced failure mode. In the extreme, the resistance may become so high that the capacitor appears to be an open circuit. GA-ESI's in-process and acceptance tests of metallized capacitors include pulse discharge tests that are designed to reveal defects in the metallization and terminations that might lead to premature failures in the field. The resulting failure rate in the field is quite low in comparison to that of foil capacitors.

III. SUMMARY

Significant expansion of the operating envelope for self-healing capacitors has been described. Self-healing capacitors provide the highest energy density or longest lifetime at a given energy density. Self-healing capacitors can be safely scaled to very large energies per unit. Reliability of self-healing capacitors is much higher than that of foil capacitors when they are used within their ratings. Parameters in which foil capacitors remain predominant are discharge rate, specific power, and maximum voltage rating.

IV. REFERENCES

[1] Andrew Bushnell, GA-ESI Power Systems Department, private communication, July 12, 2006.
[2] http://www.celem.com/datasheets/CPRI400P.pdf, Celem Power Capacitors, Israel, 2007.

V. ACKNOWLEDGEMENTS

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