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Abstract

This paper will describe how film capacitors with energy densities of greater than 1 J/cc and suitable for millisecond discharge applications requiring limited life have been characterized. A variety of polymer films were tested in “model” capacitors storing and delivering hundreds of Joules of energy at voltages of 2-10 kV. Self-healing metallized film electrodes were utilized in these designs to achieve electric fields greater than 500 MV/m. Maximum operating voltage for short-term and long-term use was determined. Life tests were then performed with the goal of achieving at least 1000 charge/discharge cycles at maximum energy density. Degradation and failure of the capacitor samples was determined by measurements of capacitance and dissipation factor. Failure modes in continuous dc, normal charge/discharge pulse service, and short-circuit fault conditions were determined. Design modifications to increase life and energy density were made based on those analyses. Scale-up of the individual unit energy to 100 kJ is underway.

I. INTRODUCTION

Capacitors are used as energy storage and energy discharge components in many pulse power systems. For high energy (>1 kJ), high voltage (> 1 kV), and high peak current (>1 kA) requirements, wound film capacitors are generally used. Very high peak power and average power densities can be achieved using discrete foil electrodes in combination with film dielectrics [1]. High energy densities are obtained using self-healing metallized electrodes vapor deposited on polymer film dielectrics. The highest energy density film capacitors are generally oil-filled (vacuum impregnated) with a liquid dielectric to suppress partial discharges and surface arcing, as well as to increase capacitance [2].

The energy density of a capacitor is given by the equation

$$ED = PF * \epsilon_0 * K * E^2 \quad (1)$$

Where PF is the packing factor (ratio of volume actually storing energy to total volume), ϵ_0 is the permittivity of free space, K is the so-called dielectric constant, and E is the effective voltage gradient within the dielectric. The packing factor of large film capacitors is typically in the range 50-70%. A limited range of high quality polymer films are available from which to wind capacitors, resulting in dielectric permittivity ranging from 2 to perhaps 10 [3]. Depending on the application, the choice of polymer films may be further limited by constraints on energy efficiency (dielectric loss), temperature range, and cost. Therefore, increasing the energy density of film capacitors is often a matter of increasing the voltage gradient, E. Due to the phenomenon of dielectric aging, this is effectively trading off lifetime for energy density.

In the present work, several metallized film dielectrics that were developed for applications requiring lifetimes of tens of thousands to millions of charge/discharge cycles were tested for their energy density capability in pulse power applications requiring a minimum of just 1000 charge/discharge cycles. The objective was to determine the maximum energy density of these dielectrics under a specific set of conditions.

II. SAMPLES

The capacitor samples selected for study were wound metallized film, self-healing capacitors in drawn metal cans. All were vacuum impregnated with an appropriate dielectric liquid. In some cases, samples with two different liquid impregnants were prepared for comparison of the performance with this single change in design. The dielectric materials included commercial and custom-made polymer films, Kraft paper, and combinations of Kraft paper with polymer films. The nominal voltage ratings given to the samples for their original, longer-life applications ranged from 1.6 kV to 5.3 kV. The energy stored in the individual samples at their rated voltages ranged from 128 to 576 Joules.



Figure 1. Photograph showing capacitor samples

III. TEST METHODS

In order to determine the capability of each type of capacitor, a variety of destructive tests were employed. These tests were designed to stress the capacitor samples in different ways and provide clear indication of how the capacitor degraded with each type of stress. The tests included a Maximum Voltage Test, a Short-Circuit Current test, a Stepped Stress Pulse Life Test, a Fixed Voltage Pulse Life Test, and a DC Life Test. Post mortem failure analyses were performed to determine modes of failure and provide a basis for improvement of the designs and manufacturing processes.

A. Maximum-Voltage Test

The Maximum Voltage Test was designed to rapidly determine the absolute maximum DC voltage capability of each design. The test was a short-term, stepped-stress test with voltage applied for 60 seconds at each step. The initial step level was the rated voltage of the design, and subsequent steps were 100 Volts greater than the preceding step. The samples were discharged completely between steps and measurements of capacitance and dissipation factor (DF) were made to determine the level of degradation of the sample resulting from loss of electrode area. One sample of each design was tested.

B. Short-Circuit Test

Metallized electrode capacitors are susceptible to current-related failure modes due to the small thickness of the electrodes and the use of non-metallurgical bond terminations (end spray or scooping). When subjected to external fault modes, metallized electrode capacitors can fail open-circuit, lose a significant fraction of their capacitance, or increase in DF and ESR. The Short-Circuit Test was used to measure the maximum current density capability of the different capacitor samples. The capacitors were charged to the initial test voltage, typically 100 V, and discharged through a mechanical

relay type switch with no added resistance or inductance in the circuit. The underdamped discharge was observed using an oscilloscope and the peak current and other waveform parameters were recorded. The charge/discharge cycle was repeated five times at each voltage level. The samples were then removed from the circuit and their capacitance and DF were measured. The charge voltage was increased by 100 Volts and the process repeated, unless the measurements indicated capacitor failure due to capacitance loss or increase in DF.

C. Stepped-Stress Pulse Life Test

While the Maximum Voltage Test would set an upper limit for dielectric withstand voltage, the Stepped-Stress Life Test was designed to measure the maximum voltage at which a given design would perform reliably for 1000 charge-discharge cycles. The capacitor was charged to voltage in under 5 seconds and held at voltage for 1 second prior to discharge. The charge/discharge sequence was repeated just once per minute to avoid overheating. The discharge circuit characteristics were not intended to closely simulate a specific application, but only to ensure that peak current densities in the metallized electrodes were well below design values. This was intended to ensure that failure modes would be voltage-driven and not current-driven. The samples were tested for 1000 shots at their rated voltage, capacitance and DF were measured, and then the voltage was increased (by 100 or 200 Volts, depending on rated voltage), and the process repeated. The test on a sample was halted when capacitance loss exceeded 5% of the initial value. Three samples of each design were tested.

D. Fixed Voltage Pulse Life Test

The stepped-stress life test provided cycle life data that could be used to estimate the maximum voltage at which each capacitor design would reliably operate for 1000 charge/discharge cycles. The Fixed Voltage Life Test was then performed at that voltage to measure the actual cycle life. This additional step was considered necessary because of the possibility of significant dielectric aging at lower voltages, as well as the possibility of a voltage conditioning effect on the dielectric, such as through space-charge formation due to ionic conduction.

The same cycle timing and discharge circuit were used for this test as were described for the Stepped-Stress Life Test. Three samples of each design were tested initially.

E. DC Voltage Life Test

Selected designs were life tested at a fixed dc voltage to determine the capability of these designs in applications requiring longer charge time or hold time during each cycle, and to determine the failure mode under steady-state conditions. Comparison of the life and failure mode with those obtained under pulse test conditions was expected to provide useful information about the fundamental aging process.

IV. RESULTS

A. Maximum-Voltage Test

The capacitance measurements made during the Maximum Voltage Test are shown in Figure 2.

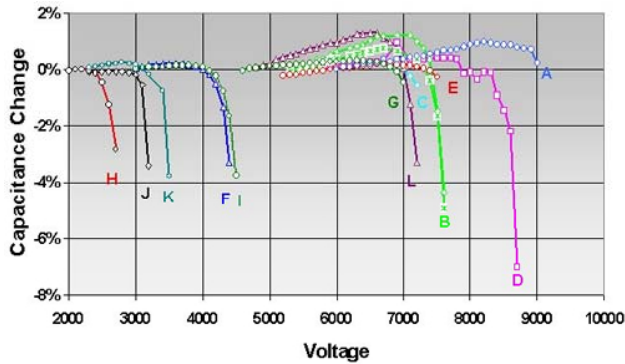


Figure 2 Maximum Voltage Test

The capacitance initially increases as the applied voltage produces electrostatic attraction between the opposing electrodes, forcing them closer together. The oil-filled space between films is constricted. (The effect is observed after removal of the applied voltage, through capacitance measurements made at low voltage using a digital LCR meter, as relaxation occurs over hours or even days.) Self-healing events begin to occur very frequently at the highest voltages, resulting in measurable capacitance loss.

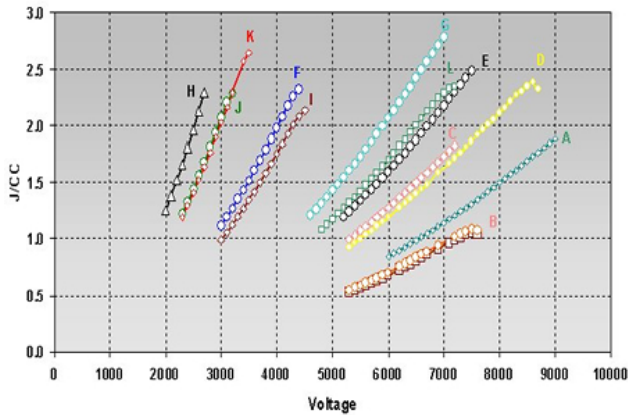


Figure 3. Energy density versus voltage.

Because of the variety of dielectric types and dielectric thicknesses used, it was found useful to plot the energy density versus the test voltage, as shown in Figure 3. The delivered energy, J , was estimated using $J=1/2*Co*V^2$, where Co was the capacitance value measured at low voltage and V was the prior test voltage. The volume of the capacitor samples was calculated using measurements of the external dimensions, not including bushings or small protruding features on the cans. There was one exception, in which the sample wound element did not fit tightly inside the can, for which an estimated volume for a

better package design was used in the calculation of energy density.

B. Short-Circuit Test

Results of a typical short-circuit test are shown in Figure 4. The capacitance and dissipation factor are stable until a critical threshold peak current value is reached, at which point capacitance decreases, DF increases, and the peak current begins to decrease, even as voltage is increased on subsequent steps of the test. High current density in the metallized electrodes causes fusing at defects and high resistance interfaces. Capacitance loss results from areas of the electrodes becoming isolated due to either “electrode fractures” or end spray disconnection. DF increases are caused by the same phenomena, but indicate that the current path lengths to the remaining electrode areas have become elongated or even tortuous.

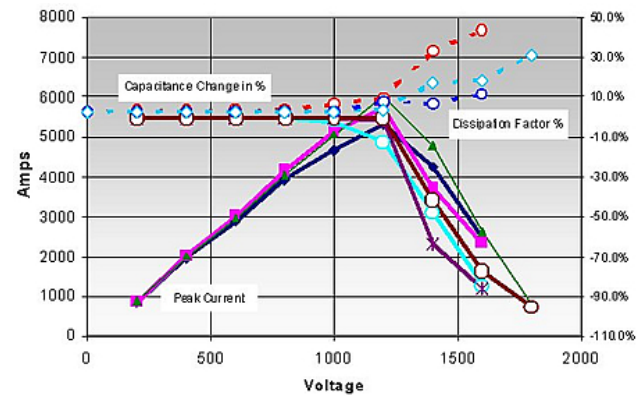


Figure 4. Typical Short-circuit Test results.

Analysis of the resulting data was complicated by the fact that off-the-shelf units were used for these tests, and construction techniques varied from design to design. Specifically, some designs had end spray covering the entire exposed edge of the metallized electrodes, while others had portions that had been masked off to aid in drying and impregnation. This results in enhanced current densities at the edges of the end-sprayed areas. Capacitors designed for maximum current-carrying capability are fully end-sprayed. An additional variable is the width of the metallized electrode, which determines the aspect ratio of an element of a given electrode area and, thus, capacitance. The wider the electrode, the shorter the winding length, and the greater the density of current at the end spray termination. In the present study, the width of the metallized films ranged from 75 to 150mm.

C. Stepped-Stress Life Tests

During the stepped-stress life tests, an increase in capacitance after 1000 cycles at rated voltage or even higher than rated voltage was observed in some designs, but not all. The rate of capacitance degradation with increasing voltage tests varied significantly between designs. In one case, a change in voltage from 3400 Volts

to 3500 Volts resulted in the three samples tested going from zero capacitance loss to about 10% capacitance loss. In another case, capacitance loss of about 1% was observed after 1000 shots at 5000 Volts, 5% after 1000 shots at 5200 Volts, and 10% after 1000 shots at 5400 Volts.

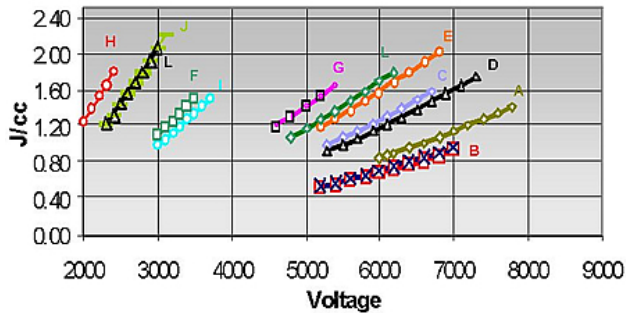


Figure 5. Energy density (J/cc) versus voltage in Stepped – Stress Life Test.

The results of all the stepped-stress life tests, depicted in terms of energy density versus voltage, are shown in Figure 6. Whereas energy densities as high as 2.5 J/cc were observed in the short-term Maximum Voltage Test, the largest energy density achieved in the Stepped-Stress Test was 2.2 J/cc.

D. Fixed Voltage Life Tests

Based on the results of the stepped-stress life tests, voltages for each design were selected for Fixed-Voltage Life Tests. The test voltage selection process was exploratory in nature and therefore results varied from 500 to 2000 cycles life depending on the design. Energy densities exceeding 2.2 J/cc for 1000 cycle life were verified.

Additional fixed voltage life tests were performed on Model E and G capacitors to determine life scaling with voltage. In the case of Model G, in tests conducted at 6.4, 6.75, and 7.0 kV, the exponent, n , on the life scaling equation, $L \sim 1/V^n$, was found to be ~ 7.0 . This value is lower than observed in previous tests on metallized capacitors, and is similar to that seen in foil electrode capacitors. The observation from post mortems that failure was driven by partial discharge erosion of the metallized electrodes, rather than by self-healing dielectric breakdowns, is probably related.

E. DC Life Tests

DC life tests were performed on Model G at 6.5 and 7.0 kV. Loss of 5% of capacitance at 7.0 kV occurred in 20 to 60 minutes, while the same level of degradation took 210 to 330 minutes at 6.5 kV. Failure analyses have not yet been performed.

V. SUMMARY

A methodology for characterizing pulse capacitors for their maximum energy density capability in short-lifetime applications has been described. A variety of metallized dielectric systems were evaluated using this approach, allowing the selection of a specific design for maximum energy density in the target voltage range. Pulse capacitors with energy densities exceeding 2.2 J/cc for lifetimes of more than 1000 shots were demonstrated and characterized. The selected dielectric is now being scaled up to a 100-kJ size unit.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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