ANNULAR FORM FACTOR FILM CAPACITORS

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Abstract

An annular form factor dry film capacitor having the minimum possible Equivalent Series Inductance (ESL) has been developed for short pulse applications requiring high currents at voltages below 10 kV DC. The annular design offers the lowest possible inductance at the system level and can be wound to a tolerance of ±1%. The narrow film width provides a low Equivalent Series Resistance (ESR) and very large contact length; which when combined with customized metallized film will support high current levels without the need for foil electrodes. Single section units can provide working capacitance values of up to 650 μF at 4 kV DC and up to 9500 μF at 1 kV DC with symmetrical discharge currents. Multiple section capacitors can also be fabricated to provide for higher voltage operation at reduced energy density. Using film widths up to 65 mm, the possible inner diameter range is from 25.4 mm (1 in) to 254 mm (10 in), with the outer diameter ranging up to 406 mm (16 in). A prototype design is presented along with preliminary data for ESR, ESL, discharge currents, and life assessment.

I. INTRODUCTION

The design of polymer film pulsed power capacitors requires compromise between energy density, voltage withstand, current capability, acceptable failure mode, life expectancy, repetition rate, and pulse duration to suit the application [1, 2]. Metallized film capacitors can provide energy densities exceeding 1 J/cc in conjunction with self-healing to ensure a "soft" failure mode. However, for high-current, short pulse (e.g. on the order of microseconds) applications, such capacitors are traditionally limited by the current density in the electrodes and end spray connections. Furthermore, the metallized film will have an unacceptably large ESR, particularly for high energy density applications requiring a long and narrow form factor. These problems can be overcome by the use of foil electrodes, which improve both the ESR and current carrying capability at the expense of reduced energy density and a "hard" failure mode when dielectric faults occur.

A novel annular metallized film capacitor has been developed to address short pulse applications requiring high currents at modest voltage levels with an environmentally friendly, lightweight, "dry" package. The large winding cross section and short axial length provide a very large contact length for the end spray in conjunction with a low ESR. These features combined with a customized metallized film can support discharge currents in excess of 50 kA without the use of foil electrodes. Single section parts are available within the approximate parameter space of 650 μF at 4 kV and up to 9500 μF at 1 kV with a capacitance tolerance of ±1%. A wide variety of physical dimensions are possible, with inner diameters ranging from 25.4 mm (1 in) to 254 mm (10 in). Equipment upgrades currently in progress will support outer diameters of up to 406 mm (16 in).

The annular capacitor allows the end user to achieve the lowest possible inductance configuration at the system level. For example, this form factor is ideally suited for driving a symmetric coaxial geometry. Similarly, components such at spark gaps, and solid-state or magnetic switches can be placed inside the capacitor bore to allow more compact designs. Given the present trend in pulsed power toward modular topologies using solid-state switches [3], a pulse capacitor rated for only a few kV is entirely practical. Furthermore, higher operating voltages can be readily achieved using a modular approach by simply stacking annular capacitors in series. Given the large values of capacitance available for a single "building block", a practical high voltage module can be readily assembled for applications exceeding 20 kV.

The annular capacitor has other commercial applications in addition to pulsed power. A clear market exists to replace electrolytic capacitors for high current bus bypass capacitors in switched mode power supplies. Similarly, compact form factor capacitors are also of interest for power factor correction. In the latter case, the ability to consistently achieve very high precision in the capacitance value offers a significant advantage. This paper presents the design of a prototype annular capacitor along with life testing subject to high current pulsed discharges. Estimates of the ESL and ESR are provided for a capacitor tested in the lowest possible inductance geometry.

II. DESIGN

A prototype annular form factor capacitor design for 500 μF is presented in Fig. 1. The part shown in the photograph is constructed using a customized polypropylene film wound on a hollow plastic mandrel with dimensions as provided in Table 1. End connections consist of an initial zinc end spray layer followed by an additional layer of tin/zinc. Further detail on the construction of film capacitors can be found elsewhere [1] and is eliminated here for the sake of brevity. A variety of packaging schemes are available, including tape wrap and epoxy potting. Various electrode terminal configurations can also be realized depending on the discharge current magnitude and symmetry requirements.

Table 1. Dimensions of the prototype annular capacitor.

Parameter	Value
Winding Inner Radius	42.50 mm
Winding Outer Radius	82.55 mm
Mandrel Inner Radius	37.50 mm
Total Outer Radius	85.00 mm
Active Length	59.75 mm
Overall Length	75.00 mm
Total Weight	1.5 kg

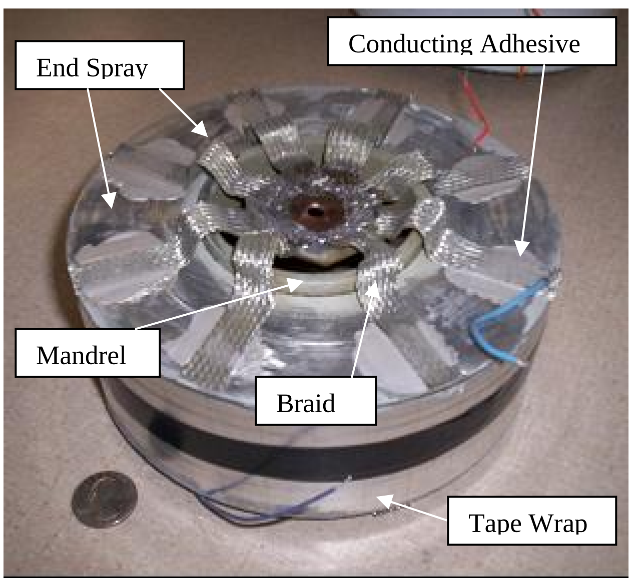

Figure 1. Prototype 500 μF annular capacitor.

The prototypes were fabricated with heavy metallization on 5.8-micron film for a minimal ESR of approximately 300 μΩ. This is achieved at a cost in self-healing capability and the voltage rating for this design is 1800 V. The coaxial inductance computed by finite element analysis for an inner conductor radius of 7.93 mm is approximately 32 nH. Assuming a safe operating stress exceeding 500 V/micron with lighter metallization, the design can ultimately support voltages approaching 2.9 kV with a higher ESR. The energy density for this case will be approximately 2.2 J/cc and 1.6 J/cc respectively for the active and total volumes with the total energy to weight ratio of 1.4 kJ/kg.

Based on the series impedance values, a peak current on the order of 60 kA is expected at 500 V when the capacitor is short circuited through a switch with a resistance of 1 mΩ. As such, the capacitor will experience significant **J** x **B** forces in both the axial and radial directions. Initial finite element analysis suggests that the respective axial and radial forces for this case will be approximately 250 N and 600 N. Testing is in progress to determine the limits for the prototype annular capacitor design as described in the next section.

III. PROTOTYPE TESTING

In order to evaluate performance of the annular film capacitor prototype design, a customized test fixture was developed. This fixture allows the capacitor to be tested in a coaxial geometry having minimal inductance and resistance. As such, the highest possible current can be extracted from the capacitor for a given charge voltage in conjunction with a severe polarity reversal, thus providing a very conservative test condition for life assessment.

A. Test Arrangement

The test setup for annular capacitor prototype evaluation is presented in Fig. 2. A symmetrical arrangement of tinned copper braids is connected to the

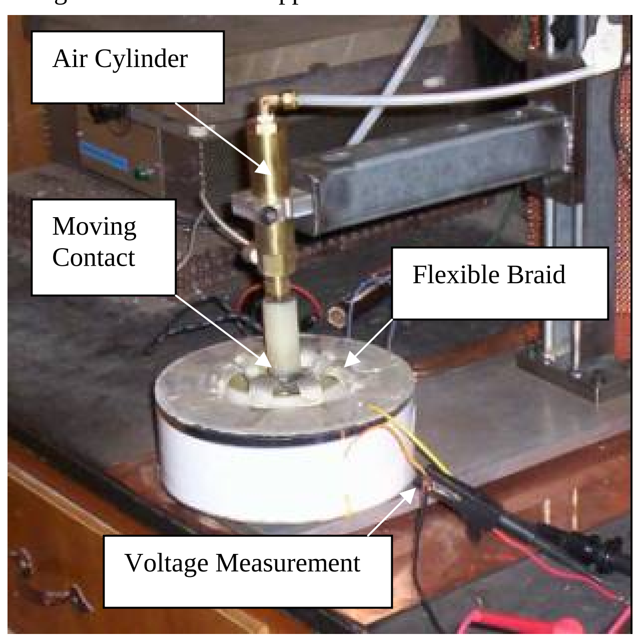

Figure 2. Illustration of the capacitor test fixture.

end spray on each face of the capacitor using a conductive adhesive. The discharge switch is comprised of tungsten alloy electrodes forming a coaxially oriented gap inside of the capacitor bore. One side of the capacitor is mounted to an aluminum ground plate and the fixed contact of the switch. On the opposite face, the copper braids are joined to the moving contact, which is actuated using an air cylinder. This approach provides galvanic isolation between the controller electronics and the experiment via the non-conducting air hoses.

The capacitor is charged through a 1500 Ω resistor from a DC power supply. Once the required charge voltage has been reached, the switch is closed for 100 ms at which point the air cylinder opens the contacts to charge for the next shot. The voltage across the capacitor is monitored using a digital oscilloscope and appropriate probe with a resistive divider to achieve the best dynamic range. The test fixture can be run in fully automatic mode with a counter to record the number of shots.

B. Preliminary Results

Two 500 μF (nominal) annular capacitor prototypes have been evaluated thus far in the test program. The first sample was tested starting well below rated voltage and the charging voltage was raised gradually in 50 V increments after 1000 shots at each level. The capacitance was measured at the conclusion of each series before going to the next voltage. After resolving some initial connection problems, a 10,000 shot series was performed at 200 V with no capacitance change outside of the measurement error (± 0.5 μF). At 300 V, contact failures were experienced at the bonds between the electrode end spray and the copper braids after approximately 1000 shots. This problem was overcome through the addition of more contact points and a high temperature cure of the conducting adhesive. A special jig was also employed to ensure uniform laminar bonds to the end spray. Note that a slight increase in the capacitance was observed as a result of the 85 °C curing process.

Repeating the 10,000 shot series at 400 V with a corresponding peak current of 48 kA did not cause any capacitance loss. A typical discharge waveform at this level is presented in Fig. 3. The total lumped series inductance and resistance to approximate an ideal under-damped RLC response are 28 nH and 1.2 mΩ, respectively. A higher order harmonic is apparent over the first few cycles of the measured voltage waveform. Possible explanations include a non-linear switch resistance, polarization effects in the capacitor and a resonance around the capacitor end face. Note that the voltage reversal is in excess of 90%, which is extremely aggressive for life evaluation.

No further connection problems were encountered until the voltage was raised to 600 V, corresponding to a peak current of 69 kA. After 30 shots

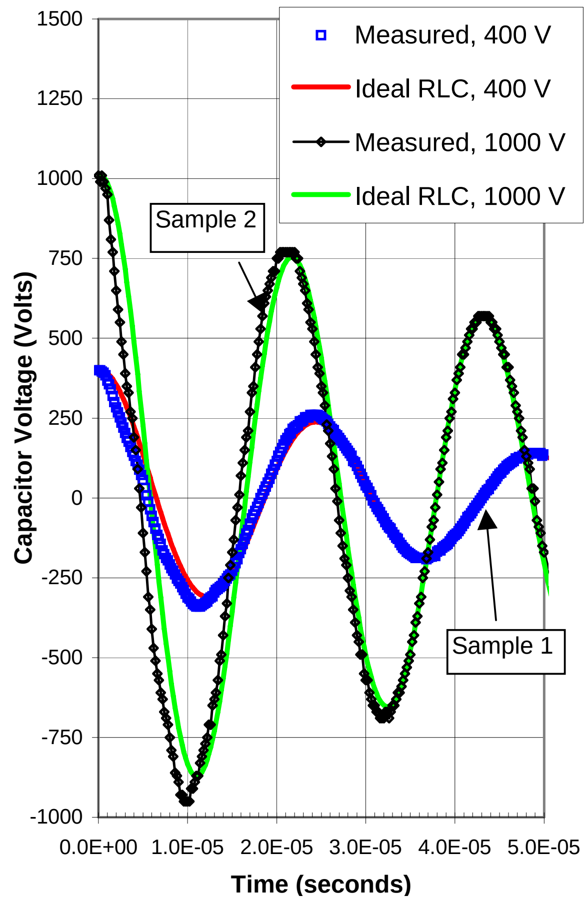

Figure 3. Typical discharge waveforms.

at this level, multiple braid connections failed at the end spray bonds. No apparent capacitance change was observed, and the braids were replaced with two additional connection points added. This modification was sufficient to reach 1000 V with a corresponding peak current of 108 kA. At this point, problems were encountered after 300 shots at the connection between the braids and the moving contact.

After modifying the braid to electrode connection, a 100:1 scope probe was used to monitor the capacitor and the resistive divider was removed from the circuit. However, this modification decreased the charging time and the voltage was inadvertently raised to 1400 V with a peak current exceeding 150 kA. The error was discovered and corrected after 45 shots. A 1000 shot series was then completed and the final capacitance for the first sample was found to have decreased by 5%. Unfortunately, the current level corresponding to the loss of capacitance cannot be determined since no capacitance measurements were made after the shots at 1400 V.

A second 500 μF sample was tested at 1000 V to evaluate capacitance degradation as a function of discharge cycles. Additional improvements to the test circuit before this run reduced the series impedance of the loop such that the peak current was 130 kA. Note that the first sample in the previous setup saw only 108 kA at this voltage with a 5% higher capacitance. A typical voltage waveform for this series after 2500 shots is presented in Fig. 3 with the capacitance reduced by approximately 14%. The respective series resistance and inductance to fit the ideal RLC discharge for the improved loop are 0.7 mΩ and 26 nH.

Life test results for the two samples evaluated thus far are summarized in Fig. 4. Based on this preliminary data, the 500 μF annular capacitor appears to be capable of discharging nearly 50 kA at 400 V for 10,000 cycles without degradation. For 1000 V with

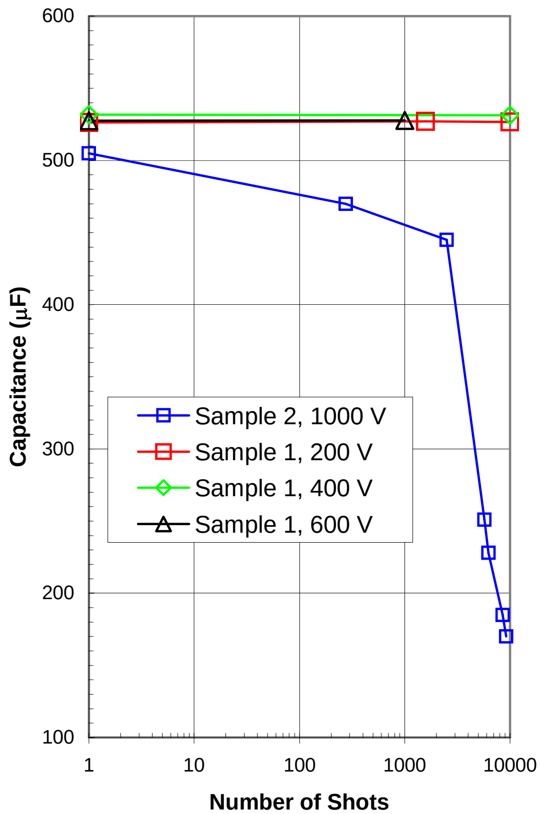

Figure 4. Preliminary life testing results.

currents approaching 130 kA, loss of capacitance becomes apparent after only a few hundred shots and the capacitance is reduced by 50% after approximately 5000 shots. Further testing is in progress to better define the operating parameters for this capacitor design.

IV. CONCLUSIONS

Prototype 500 μF annular form factor capacitors have been fabricated and tested subject to extreme short pulse discharges with more than 90% voltage reversal. Initial test results for these parts indicate that the design can handle discharge currents approaching 50 kA without degradation over 10,000 shots. Evidence of soft failure via capacitance loss becomes apparent for currents on the order of 130 kA. Additional film processing techniques are currently being explored to improve the current limit by as much as 50%.

This capacitor form factor is optimal in terms of minimizing ESR and providing large contact lengths for the end spray connections to the metallized film. Furthermore, the shape provides a very low inductance at the system level with excellent current symmetry. Prototype tests in a coaxial geometry indicate an ESR on the order of 300 μΩ and an ESL of 30 nH for the 500 μF design. Note that the ESL is also dependent upon the diameter of the conductor running down the capacitor bore.

The annular form factor capacitor offers energy densities approaching 2 J/cc in a lightweight, oil-free package. The part can be fabricated in a wide range of capacitance values and voltage ratings to support applications in pulsed power, switched mode power supplies and power factor correction. This device appears to be suitable for solid state pulsed power modulators, which can operate at less than 2 kV per stage. Furthermore, given the high capacitance values available, multiple capacitors can be stacked in series to create higher voltage modules.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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