STACKED ANNULAR FORM FACTOR FILM CAPACITORS FOR HIGH VOLTAGE AND HIGH CURRENT APPLICATIONS

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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 part is based on a multi-section design, which provides very good voltage grading between the end faces of the capacitor. This grading is preserved when using the capacitor as a building block for a stacked series assembly to realize much higher operating voltages. As such, the dielectric design of the resulting stack is greatly simplified. Furthermore, the annular form factor allows for optimal interconnections between capacitors, thus providing a high voltage capacitor stack with an ESL comparable to conventional configurations. The electrical and mechanical aspects of series stacked annular capacitors are discussed, including interconnect conductive "gasket" materials and mechanical clamping arrangements. A stacked capacitor design is presented along with preliminary test data.

I. INTRODUCTION

The use of an annular form factor dry film capacitor for high current discharge applications has been reported previously [1]. This form factor provides the minimum possible ESR and ESL while maintaining an acceptable current per unit length at the metallized film edge to end spray interface. Furthermore, the short axial capacitor length compliments the low loss performance of polypropylene film to minimize the hotspot temperature rise for high ripple current applications [2]. This capacitor geometry provides an ideal modular element for series and/or parallel combination to achieve the desired voltage and/or current ratings for various applications.

Conventional film capacitors are widely used for pulsed power and solid-state power supply applications with significant advantages of low losses and graceful aging [3, 4]. Dry film capacitors are desirable to minimize environmental impact and reduce weight, but are traditionally limited in voltage. This limitation can be overcome by series section architectures at the cost of reduced capacitance and risk of overstressing of sections due to film utilization mismatches. The ring capacitor is well suited for series combination at both the winding and device levels. The annular form factor provides very high capacitance via large active area and offers additional unique advantages as a module for creating high voltage series stacked capacitor banks.

First and foremost, the ring capacitor allows for the maximum possible current contact area across the end faces. As such, very high (> 100 kA) currents can be achieved without the need for foil electrodes, thus significantly improving the energy density. In addition, radial currents in the end spray are minimized, which greatly reduces the overall losses. Finally, the annular form factor provides a perfectly symmetric capacitor building block with well-defined axial voltage grading across each element and hence the entire stack. Note that a practical stack can be readily realized by simply stringing the capacitors onto a central dielectric threaded support rod and compressing from the ends. Note further that the ring capacitor stack can be utilized to form a coaxial arrangement with the lowest possible inductance at the system level.

From a practical standpoint, the stacking of ring capacitors requires an electro-mechanical gasket solution for interconnections between modules. While a number of options are available, cost and performance must be carefully considered in concert with the mechanical limit for compression to avoid capacitor damage. Ease of assembly, module replacement, and stack reconfiguration will also be important. Prototype series capacitor banks comprised of two 7.5 μF modules have been assembled and tested to address these practical issues. The test arrangement is discussed and preliminary data is presented.

II. TEST ARRANGEMENT

The basic capacitor design, series stack arrangement and test circuit are discussed in the following sections.

A. Capacitor Module

The capacitor "module" for the stacked bank experiments is a 7.5 μF ± 10%, eight-section metallized polypropylene film capacitor rated for 8 kV DC. The inner and outer radii for the annular part are 19 mm and 75 mm, respectively and the total axial length is 76 mm.

Each capacitor is wound on a 1/8” thick phenolic core and a tin/zinc end spray having a nominal thickness of 360 microns is applied across both end faces. The winding is encapsulated with an outer wrap of polyester tape. A photograph of the 7.5μF capacitor is provided in Figure 1.

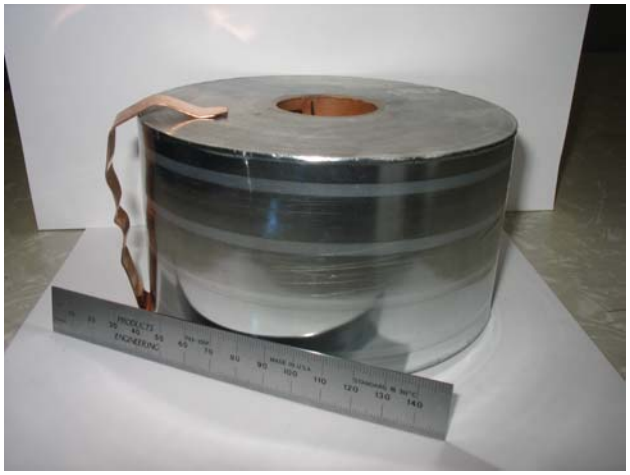

Figure 1. Photograph of the 7.5 μF ring capacitor used for stacking experiments.

B. Series Bank

The series test bank comprised of two 7.5 μF capacitor module is shown in Figure 2. Wire mesh current gaskets one inch wide (Tecknit 23-502** [5]) were applied in concentric rings to cover the capacitor end faces. The bank was clamped together using two phenolic plates connected at four points with steel threaded rod insulated by vinyl tubing. Recognizing that the minimum possible clamping force is desired to avoid damaging the end spray, hand tightened wing nuts were used to compress the stack.

C. Test Circuit

The complete test arrangement is shown in Figure 3 and the equivalent electrical circuit is presented in Figure 4. The capacitor bank is charged to the desired DC voltage through a 200 kΩ, 200 W resistor and then dumped through a pneumatic contactor with an electronically controlled repetition rate. The discharge loop is comprised of a “pancake” coil in series with the resistance of the capacitor stack and switch. Note that turns were removed from the original 10 μH coil shown in Figure 3 to achieve the desired discharge current at 1 μH. The inductive load was selected to intentionally provide a severe voltage reversal for the capacitor stack. The ringing discharge also provides multiple current spikes to the end connections and a long duration of dV/dt, to initiate significant clearings of the metallized film. The test objective was to assess capacitor performance and life subject to very pessimistic operating conditions.

Figure 2. Photograph of the series capacitor stack.

Figure 3. Photograph of the test arrangement.

III. RESULTS

Stacked capacitor samples were subjected to multiple shots at different charge voltages to assess degradation. A typical waveform for the first test stack at a charge voltage of 10 kV is shown in Figure 5. Note that nearly 100% voltage reversal has been deliberately applied. The resonant frequency of the circuit suggests an additional stray inductance of 0.5 μH and a total ESR of 15 mΩ for the discharge loop. This provides a worst-case upper limit for the ESR of the capacitor stack.

The first stack was tested at a charge voltage of 10 kV for more than 3000 shots with a capacitance loss of less than 2%. The nominal current for this case at the initial capacitance value of 3.715 μF was 16.6 kA. After testing, the current gasket was weakly welded to the capacitor end spray at multiple locations. A second stack was assembled using new capacitors and tested to approximately 10,000 shots at 7.5 kV charge.

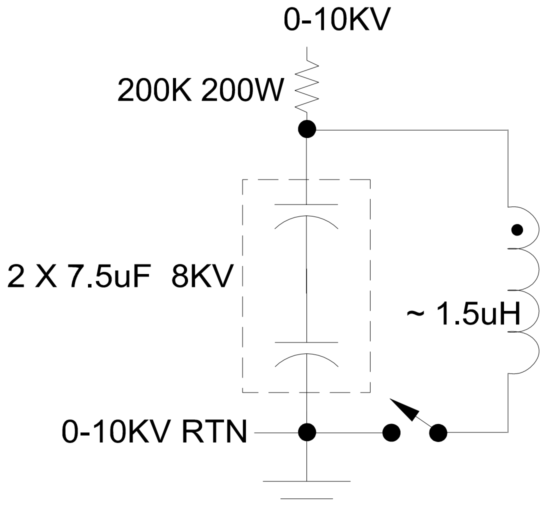

Figure 4. The equivalent circuit of the series capacitor test configuration.

The initial current for this case was 12.2 kA at a capacitance of 3.70 μF. Over the course of testing, the capacitance for the second stack was reduced by less than 1%. Further testing of the second stack was performed at 10 kV charge. After applying more than 10,000 additional shots, the capacitance was reduced by approximately 46% from the starting value at 10 kV. Severe degradation of the end spray was observed at this point. The application of 3000 more shots at 10 kV was sufficient to fail the top capacitor in the stack. Note that the bottom capacitor appeared to have sustained relatively little damage, with a total capacitance loss of less than 1%. The life testing data for the prototype capacitor stacks is summarized in Figure 6.

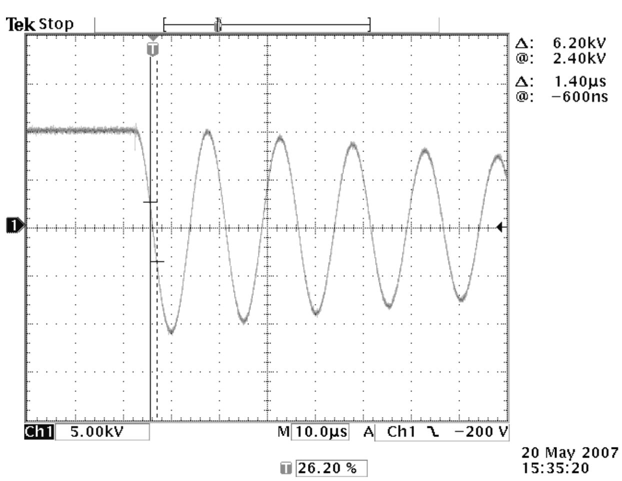

Figure 5. Scope trace for stacked capacitor discharge voltage waveform with a 10 kV charge.

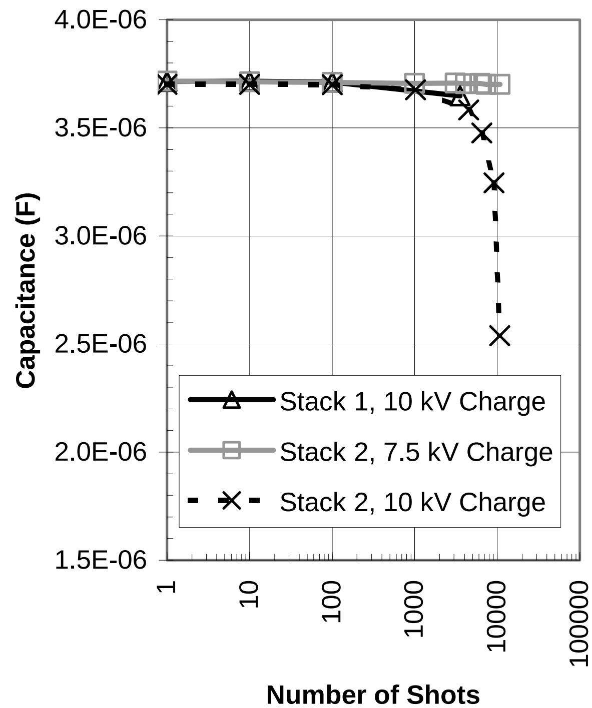

Figure 6. Compiled life data for prototype capacitor stacks.

The clamping pressure applied to the stack was evaluated indirectly by removing the compression nuts and applying weights to obtain the same equivalent average total height. For the test configuration with firmly hand-tightened wing nuts, this method suggests that the pressure was on the order of 9400 N/m^2 (1.36 psi). This operating pressure is illustrated relative to thickness versus compression data for a single current gasket in Figure 7. The ability to achieve good current joints at relatively low clamping pressures will greatly simplify the mechanical structure required for larger numbers of stacked capacitors.

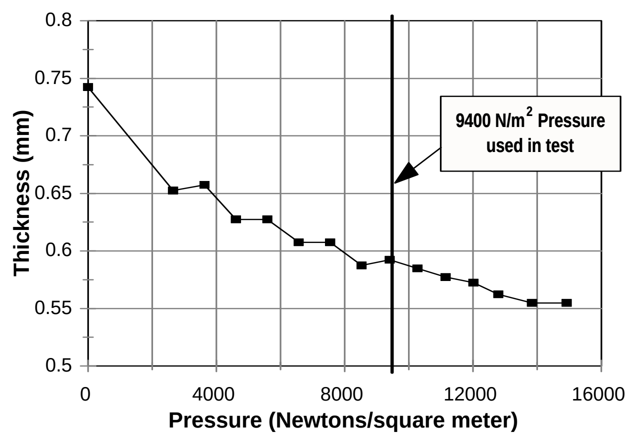

Figure 7. Measurements of current gasket thickness with respect to applied pressure (Tecknit 23-502).

IV. SUMMARY

The annular form factor capacitor offers the ability to handle very high currents using dry metallized film rather than liquid impregnated film/foil architectures. This form factor is optimal for heat transfer and offers much lower temperature rise than conventional electrolytic capacitors in solid-state power supply applications. Furthermore, the annular capacitor offers the lowest possible inductance and perfectly symmetric voltage grading at the system level. While the operating voltage has been a limit for some applications, the ring capacitor geometry is ideally suited for stacking in series to realize higher working voltages. Careful matching of the elements is clearly essential to avoid overstressing individual units.

Stacking of multi-section annular form factor metallized film capacitors to achieve higher operating voltages has been demonstrated. Series stacks of two 7.5 μF capacitors were tested up to 10 kV and 16 kA in a resonant discharge circuit providing near full voltage reversal. Under this severe test condition, capacitance loss of less than 1% was observed for 10,000 shots at 7.5 kV. At 10 kV, significant loss of capacitance (approximately 50%) occurred as the 10,000 shot mark was approached. Obvious end spray damage was followed by catastrophic failure of one capacitor during the application of 3000 additional shots. As might be expected, the second capacitor showed very little damage.

Commercial wire mesh current gaskets were found to perform adequately for this application with relatively small clamping pressures (less than 2 psi) applied to the stack. While minor welding of the gasket wires to the end spray occurred at 16 kA over 3000 shots, the stack could be readily dismantled and reassembled. These results are significant in that excellent high current performance can be achieved without excessive compression of the capacitors, which is a concern for damaging the end spray. Furthermore, the demonstration of wire mesh gaskets is important for cost savings as compared with more expensive polymer solutions. This suggests that a high voltage series capacitor bank can be constructed using an internal support member such that the replacement, addition, or removal of individual capacitor modules can be readily achieved.

V. REFERENCES

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