CERAMIC-POLYMER COMPOSITE CAPACITORS FOR COMPACT PULSED POWER APPLICATIONS

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Abstract - The U.S. Department of Defense vision for future weapons systems requires the development of electrical pulsers that exceed current state-of-the-art in energy storage density by an order of magnitude or more. Alternatives to conventional wound polymer film and single layer ceramic capacitors are needed. Composite dielectric materials consisting of ceramic nanoparticles in a polymer matrix show promise for attaining the desired increase in energy storage density. Attributes of the polymer (high dielectric strength) and the ceramic (high dielectric constant) can be attained in a single composite dielectric material. Further, fabrication approaches involving casting of the composite offer opportunity for unique form factors, high reliability and low cost manufacturing.

TPL Inc. and colleagues have teamed to investigate the limits of these new materials for use in high energy density and high power capacitor designs. This paper reports on the development progress of the composite dielectric capacitors for high voltage (50 kV-Class) and high power (>10 MW/J) application. Sub-microsecond pulse discharge life as a function of the charge voltage is compared for four design iterations. Changes in the dielectric formulation, design and manufacturing process have yielded a 1,000x improvement in pulse discharge life and refinement of other critical capacitor characteristics.

I. INTRODUCTION

Future pulse power systems require compact energy storage in order to find a practical implementation. While the fundamental pulsed power principles are reasonably well understood and have been demonstrated, the challenges arise in scaling these principles to an energy delivery system of acceptable size and weight. For high power applications (> GW) there are at least two commercially available capacitor technologies capable of producing the required discharge powers: oil/paper/film/metal foil windings [1] and lower inductance $SrBaTiO_3$ single layer ceramic blocks (e.g., ñdoor knobò capacitors [2]). Typical energy densities achievable by these technologies are 0.1 J/cc and 0.05J/cc, respectively. Innovative approaches that incorporate advanced dielectrics and novel capacitor designs are necessary to develop pulse power subsystems of acceptable size.

TPL has been developing nanocomposite dielectrics to address the need for compact energy storage and enable a range of pulsed power technologies. TPLôs unique designs, materials and supporting processes offer the opportunity for an order of magnitude reduction in capacitor mass and volume for pulse power systems. TPLôs technology is based on high dielectric constant composites comprised of formulated polymer resin systems and nano-size ceramic particles. Figure 1 includes microscope images of TPLôs 50 nm titanate powder (left) and cross-section of the ceramic-polymer composite (right). The high energy density of the nanocomposites results from the combination of high dielectric constant and dielectric strength. To date, TPL has demonstrated materials with a dielectric constant that is fifteen times greater than conventional polymers, Ů = 50 versus Ů < 3, with nearly equivalent dielectric strength, V/t = 350 kV/mm. This combination of dielectric constant and dielectric strength supports an intrinsic material energy density of 27 J/cc.

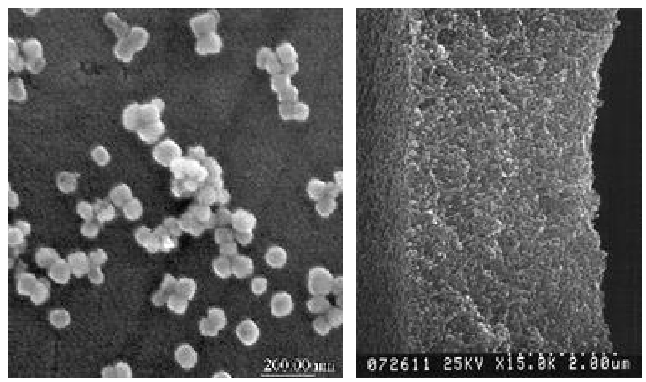

Figure 1. SEM image of TPLôs ceramic nanoparticles (left) used in preparing the ceramic-polymer dielectric (right)

This paper presents recent development progress made on on TPLôs ceramic-polymer composite capacitors for high-power (GW), fast-discharge (< 100 ns) applications. For this development effort, the nominal design is based on a multi-layer construction with a capacitance between 6 and 10 nF and pulse operating voltage between 40 and 90 kV. Evaluation of the discharge characteristics and life was established for peak power output in excess of 100 MW. This review involves summarization of development in three general areas: dielectric materials, processes, and capacitor design. This paper reports on the current status, results to-date and continued development aspects.

Initial development of TPLôs nanocomposite dielectric began with basic experiments to produce a material system that could be cast into simple capacitor geometries and identify intrinsic electrical properties such as voltage strength and dielectric constant. This early development effort focused on addressing issues related to composite material processing and electrode material selection and preparation. Evaluations were performed in simple, single-layer capacitor structures, with nominal capacitance values of 1.0 nF and a breakdown voltage between 50 and 100 kV. Typical dielectric layer thicknesses for these devices were between 0.5 and 1 mm. A variety of dielectric material process parameters were varied, including nanoparticle dispersion, filtering, and pressure-temperature conditions during casting and curing. In addition, electrode material and processes for finishing the surface and edges were adjusted to reduce electric field enhancements at electrode edges. The result of the process and design optimization was single layer capacitors with average voltage stress capability of 150 kV/mm. The typical measured dielectric constant of this material was 50, corresponding to a material energy density of approximately 5.0 J/cc.

Single layer capacitor development was then transitioned to a multi-layer design, representing a relevant energy storage component that could be used to bench mark capacitor performance for the first generation of nanocomposite dielectric capacitors. Subsequent development has focused on identifying and addressing performance limitations related to operating voltage, reliability, temperature and voltage dependence and pulse life. Three significant iterations of material, design, and process development representing the first three generations of nanocomposite dielectric capacitors followed. Presented here is the development and performance of the fourth generation.

II. CAPACITOR DESIGN AND FABRICATION

Development of the ceramic-polymer composite capacitor has focused on high capacitance (6 to 10 nF) geometries with high packaging efficiency. Thus, a low inductance multilayer design has been pursued. The multilayer geometry increases electrode area in a compact manner, facilitating capacitance scaling to a useful value for Marx bank applications. A CAD rendering of a prototype multi-layer design is shown in Figure 2. The nominal size of the prototype device is approximately 6 x 6 x 2 cm. Note that this geometry can be scaled to the desired voltage and capacitance by adjusting the number of electrodes, electrode area, and electrode separation. The fabrication process involves assembling the electrode structure in a mold and infiltrating that structure with the nanocomposite dielectric. The resin, which is thermal setting, is then cured. The final component is cast to net shape and is comprised only of the conductors and nanocomposite dielectric.

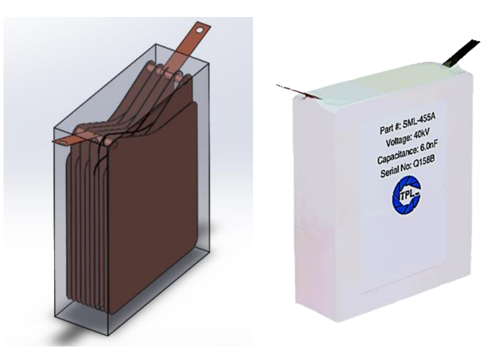

Figure 2. Schematic and photograph of the multi-layer, composite dielectric capacitors, left and right respectively

III. PROGRESS IN MATERIAL, PROCESS & DESIGN

TPLôs nanocomposite dielectric is formulated using TPL produced nanopowders and thermal-setting resin systems. By producing the raw materials internally TPL has had the opportunity to tailor each individual component of the dielectric to optimize performance. Continuous improvements have been undertaken to maximize the intrinsic energy storage capability of the dielectric system. While the fundamental approach to producing polymer-ceramic nanocomposite dielectrics has not changed, refinements to the material, process, and design continue to result in significant performance gains relative to early generations of the technology. The result is a commercially viable capacitor technology that can provide improved performance over the current state-of-the-art in commercially available capacitors for high-power fast-discharge applications.

Specific improvements to the fourth capacitor generation have been introduced. Resin formulations have been customized for increased operating voltage, operating temperature range as well as reduced capacitance dependence on temperature and voltage. Powders treatments have been introduced to achieve a crystal lattice structure for increased dielectric constant and removal of residual ionic contaminants remaining from the synthesis. The result is a 20% increase in capacitance and a 50% reduction in dielectric loss over the first three capacitor generations. Finally, methods for dispersing the nanopowders in the resin system have been refined for improved flow characteristics which reduce potential for the introduction of defects during the capacitor casting process.

Pilot-production fabrication techniques have been established for batch processing of multiple capacitors. Concurrently, reliable processes have defined to achieve consistent performance and high yields. Molding and infiltration approaches have been improved to reduce casting related defects and to accommodate material shrinkage during cure to minimize residual stress within the final capacitor. Fabrication methods have been scaled to a level which supports transition to an entry-level, commercially product.

While the first three capacitor generations used stainless steel electrodes and internal hardware to create and support the capacitor structure, the latest design eliminates the need for any secondary hardware to remain inside the capacitor. This internal support hardware had to be accommodated by modifying the shape of the electrode to control the effect of electric fields, the result of which was a reduction in the effective active area of the capacitor and a loss in overall capacitance, as well as creating variability in the electrode registration due to the complicated assembly procedure. The fully floating copper electrodes in the 4th generation design reduce stress by accommodating material shrinkage during cure; increase capacitance as all the available area in the volume of the capacitor can be used for energy storage; and improve integration by allowing the use of soldered connections rather than mechanical; and a reduction in cost due to a reduction the assembly hardware and simplified construction process.

IV. TESTING & EVALUATION

The capacitance behavior of the nanocomposite capacitors were characterized as a function of temperature and voltage. LCR measurements were made using HP 4284A on capacitors in a Tenney environmental chamber. As shown in Figure 3, the capacitors demonstrate a positive but largely independent temperature coefficient from -55 to 65 °C. Capacitance measured at 1.0 kHz changed by approximately ± 10% from 25 °C over the temperature range. Capacitance was also determined as a function of DC bias voltage. Impedance measurements were made on capacitors connected to a component network that provided both DC blocking and AC isolation. As shown in Figure 4, the capacitors demonstrated a negative but largely independent voltage coefficient. Capacitance measured at 1.0 kHz changed by less than 10% up to 50 kV. Overall, these measurements indicate the nanocomposite capacitors provide stable energy storage over a broad range of operating conditions.

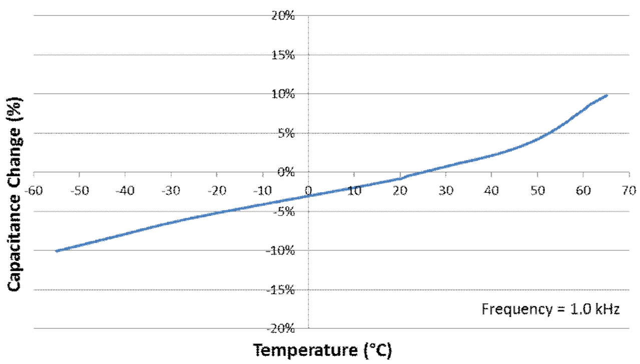

Figure 3. Capacitance change with temperature, -55 to 65 °C

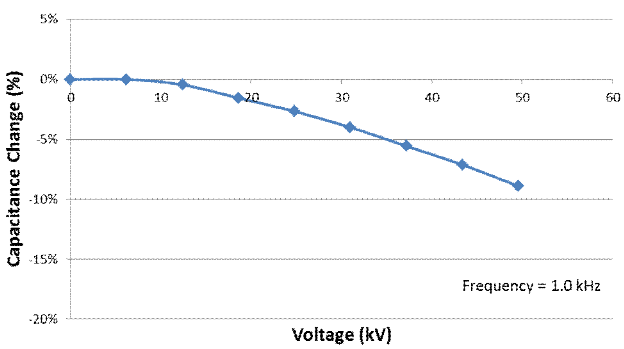

Figure 4. Capacitance change with voltage from 0 to 50 kV

Pulse discharge testing of the nanocomposite capacitors was performed using a high voltage configuration depicted in Figure 5. In this system, a Glassman LX series 150kV power supply charges the device under test though an isolation resistor that also determines the charge current and charge time. The voltage on the device under test (DUT) is monitored via a Northstar VD-200 resistive probe. The DUT is discharged through a series combination of an inductor and resistor via a spark gap. Repetitive charge-discharge cycles used in pulse life testing is achieved with a constant charge current which provides a frequency of 10 Hz. The load current is monitored via a T&M Research coaxial CVR. The CVR data is recorded by a Tektronix TDS3000B series oscilloscope.

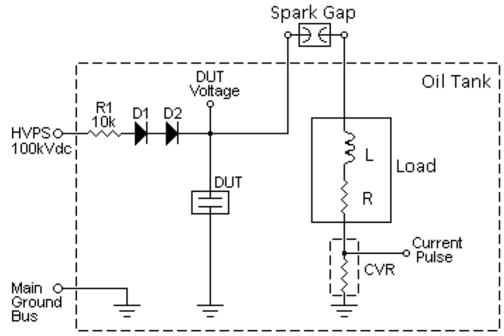

Figure 5. 100 kV RLC circuit used for capacitor life testing

Measured current and voltage output from the nanocomposite capacitors indicate capability for very high power discharge. Figure 6 shows a representative discharge from a 9.6 nF capacitor into the standard load which results in a 65 ns FWHM that is nearly critically damped. The 4.5 kA ouput into the 5.45 q load equates to a peak power of 110 MW or 18 MW/J. This measured output was found to be consistent with the modeled discharge behavior and the anticipated output energy, accounting for the minor loss in capacitance at voltage. Further, the data show that the discharge characteristics are stable through the capacitor life.

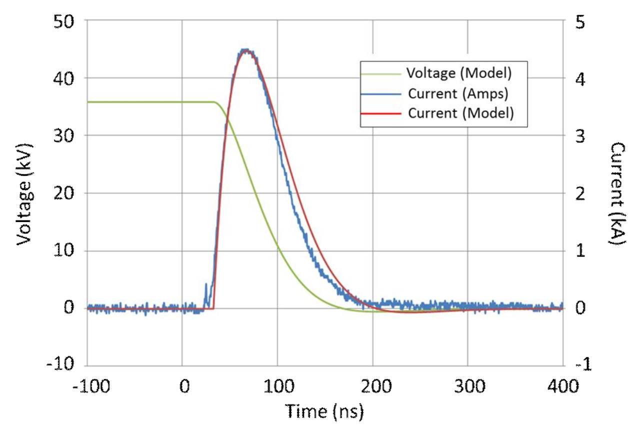

Figure 6. Discharge voltage and current measured on a 4th generation 9.6 nF capacitor into a 110 nH, 5.45 q load

Refinements to the nanocomposite capacitor continue to provide improved performance, as defined by the operating voltage and pulse life. Figure 7 shows the averaged pulse life data on four generations of capacitors, 1st through 3rd generation previously reported [3-5]. Pulse life tests on over 50 fourth generation capacitors highlight the recent improvements material, process and design improvements noted in Section III. Capacitor pulse life between 20 and 40 kV has been increased by three orders of magnitude relative to the 1st and 2nd generation and by two orders of magnitude relative to the 3rd generation. Alternatively, the voltage for a pulse life between 10^3 and 10^4 has been increased by 100% relative to the 1st and 2nd generation and by 40% relative to the 3rd generation.

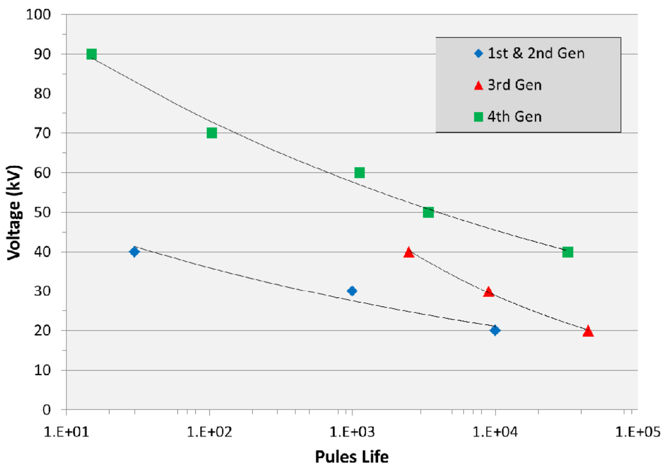

Figure 7. Discharge life testing results with power law curve fits, illustrate increased voltage and pulse life with continued capacitor development

Typical capacitor failures in life tests are defined by dielectric breakdown followed by a low resistance inter-electrode fault path. Figure 8 is a photograph of a representative failure site at an electrode edge.

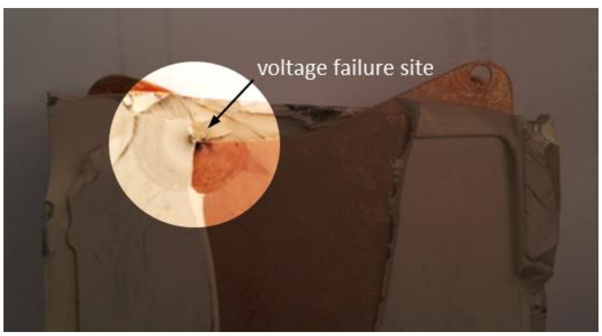

Figure 8. Dielectric breakdown of capacitor at electrode edge associated with electric field enhancement

V. SUMMARY AND FUTURE WORK

Currently, the finished devices produced by this investigation consistently achieve greater than 0.5 J/cc energy density at maximum test voltages, representing a factor of 5 to 10 improvement over other commercially available high power capacitor technologies. However, significant work remains to achieve 1 J/cc energy density with high yields and useful device lifetimes. Ongoing development will focus on reducing the shot life dependence on voltage to improve reliability and life at higher operating voltages. To address the voltage dependence it will first be necessary to de-convolute what parameters have the most significant impact. Separating the effects of material, design, and process will need to be performed, and once the primary parameter is identified, what factors modulate the voltage dependence within that parameter will be investigated. In addition, investigation of high power discharge and lifetime performance of these devices will be completed. Subsequent scaling of device capacitances to values more useful for high energy Marx bank applications (e.g., 80nF to 100nF, as shown in a scaled 85 nF prototype in Figure 9) and application of this dielectric material to other compact pulsers (e.g., stacked Blumleins) may then proceed.

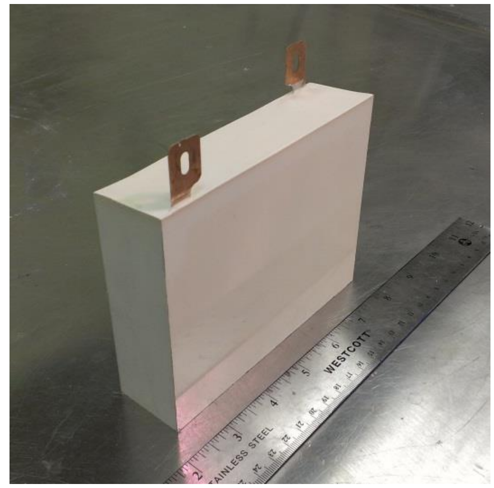

Figure 9. Photograph of scaled composite capacitor at 85 nF

VI. REFERENCES

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