Compact, Very High Voltage Capacitor Development Based on Advanced Machinable, NanoDielectric Materials

S. A. Dickerson, R. D. Curry, S. A. Mounter, L. J. Brown
Center for Physical and Power Electronics
University of Missouri-Columbia
Columbia, MO, United States of America
CurryRD@missouri.edu

***Abstract*— The University of Missouri has been developing compact capacitors for use in high voltage pulsed power/directed energy applications. The dielectric employed in this development is a proprietary nanocomposite, nanodielectric material - MU100. The material was originally developed for use in dielectric loaded antennas; however, due to various material properties, the nanocomposite has shown promise in development of compact high voltage capacitors. Prior work has shown small scale samples of the high permittivity nanocomposite dielectric material to have an average dielectric strength of 225 kV/cm with peak breakdown fields in excess of 325 kV/cm. When scaling up to accommodate application specific voltages, failure modes become more pronounced due to volume effects of the nanocomposite and field enhancement factors at the electrode dielectric interfaces. This paper describes how the material was scaled from small scale samples up to compact capacitor prototypes capable of repeatable performance at 250 kV to 500 kV with lifetimes greater than 10^4 shots.**

Keywords*— *Nanodielectrics, Dielectric, Capacitors, High Voltage, Nanocomposites, Pulsed Power System.

I. INTRODUCTION

Capacitors are crucial to the energy storage needs of nearly all pulsed power and directed energy systems being fielded today. Current capacitor technology is a large, if not the primary, contributor to these systems, often times, large size and weight. In order to make these systems more practical for actual field use, the energy storage systems must be significantly reduced in size and weight. High energy density capacitor development is the forefront of this size reduction effort. At the University of Missouri, a successful effort on this front has been built on a proprietary polymer – nanoceramic, nanodielectric composite known as MU100.

The MU100 nanodielectric was developed to reduce the size of high power antennas using dielectric loading [1]. Due to material properties, the nanodielectric has shown it is a promising media for reducing the size of high frequency, high voltage capacitors as well [2-3]. The past few years have focused on development of small scale, MU100 capacitors. [4]. That development has yielded small scale capacitors with an active dielectric constant near 200 at relevant frequencies and dielectric strengths of 100-250 kV/cm on average.

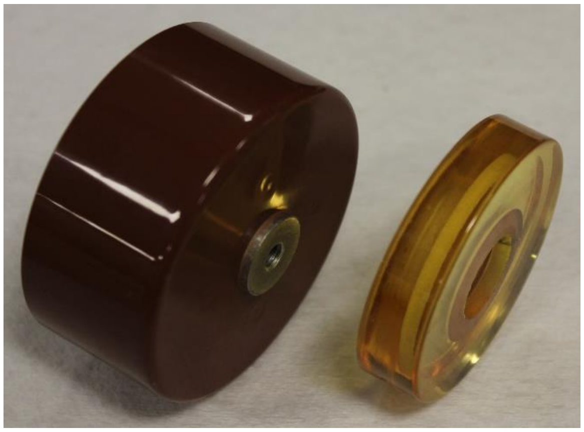

Fig. 1. A small scale MU100 capacitor (right) shown side by side with a commercially available TDK door knob capacitor, both of which are rated at 40 kV. The MU100 based devices are considerably smaller.

However, to make this technology useful to the pulsed power and directed energy communities, the size of the devices must be increased. Small-scale capacitors (rated at about 40 kV) have been scaled up to functional devices capable of long life (10^5-10^6 shots) at 250 – 500 kV depending on the capacitor configuration [5].

Scale up of the manufacturing process to produce the 250-500 kV capacitors led to an increase of the dielectric constant from 100 to 200. Additionally, the development of the ultrahigh voltage capacitors was used to optimize the electrode topology and potting methods. To increase the size of the capacitors, the fabrication process was also optimized to reduce the presence of volume dependent defects. Advanced electrode geometries were also developed to reduce the field enhancement factor and thus, the electric field at the triple point formed by the encapsulant, nanodielectric material and electrode. The remainder of this paper will present the details of how the technology was scaled from a small scale sample to a full scale, 500 kV long lifetime capacitor prototype.

Work supported by the JNLWD under contract number W15QKN-14-9-001

II. SCALING

It is well documented that dielectric strength drops according to an inverse power law as thickness of the medium is increased. [6].

$$E(d) = kd^{-n} \tag{1}$$

Where E is the applied electric field at breakdown, d is the dielectric thickness, and k and n are constants associated with a specific material.

This phenomenon was seen in MU100 when scale up of the material was initiated. However, it is still unclear, due to the nanocomposite nature of MU100, if the material's decrease in dielectric strength with thickness is due to macroscopic volume effects (a larger probability of voids or material defects with increased material volume) as in [7-10], or if the decrease in dielectric strength with thickness is due to a more microscale phenomena of surface charge injection from the electrodes, which can lead to generation of conductive channels within the dielectric material matrix [11-14]. Since reduction in MU100 dielectric strength with thickness is observed, to effectively scale up the material from small scale test samples to full scale capacitor elements, both breakdown mechanisms must be accounted for until more research determines which physical process (volume effects or charge injection) is the primary determination of voltage breakdown.

The refinements to the MU100 manufacturing procedures made in the process of scaling the MU100 material from 2.54 cm diameter, 0.15 cm thick samples up to 3.4 cm diameter, 2 cm thick substrates were crucial in development of a platform upon which ultrahigh voltage capacitors could be developed. The scaling process resulted in full scale MU100 with a dielectric constant 60%-80% higher than the initial small-scale embodiments.

III. CAPACITOR DEVELOPMENT

After scaling of the MU100 nanodielectric material to larger capacitor sizes, full scale MU100 capacitor development focused on reducing the enhancement at the electrodes, and assembly. First, development of an advanced field shaping electrode topology to reduce field enhancement factors (FEF's) was completed. Second, the design of the compact ultrahigh voltage capacitor itself was completed, coupled with a method of dielectric assembly or forming sub-element capacitors into a ruggedized final capacitor. Finally, an advanced encapsulation process was developed to ensure long lifetime functionality and to add mechanical stability to the ultrahigh voltage MU100 capacitors.

A. *Field Shaping Electrode Development*

Nearly all of the dielectric breakdowns observed during the small-scale testing and initial scaled testing were edge breakdowns. These tests were conducted at 40kV, 100 kV, and 250 kV utilizing existing test stands. The electrode edge breakdowns suggested that field enhancement at the triple point was the primary cause of device failure [15]. The breakdown due to the FEF resulted in breakdown at the surface of the MU100 substrate and at the encapsulant interface with the nanodielectric surface. To mitigate the (FEF's), a corona ring electrode was designed to hide the triple point and to spread the high electric fields present at the electrode, nanodielectric, and encapsulant triple point interface [16]. The design of the field shaping electrode utilized a 3D electromagnetics code, CST's EM studio, to simulate the various corona ring configurations.

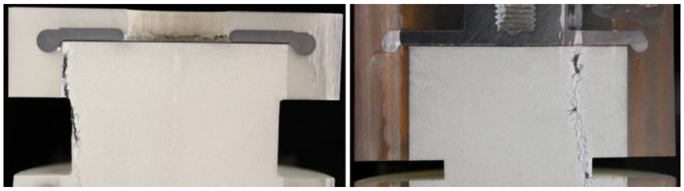

Fig. 2. Physical shortcomings of the first-generation field shaping electrode (left) did not mitigate edge breakdowns. Design and incorporation of the final field shaping electrode design (right) moved the breakdown into the bulk of the MU100 capacitors.

Simulations showed the field shaping electrode is responsible for a FEF reduction of 4.5 times the average electric field.

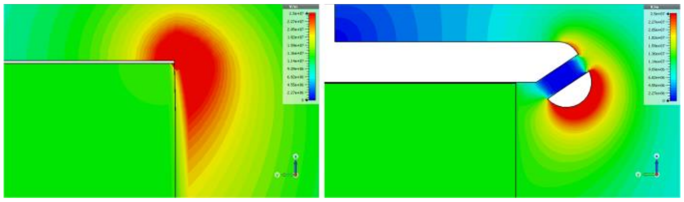

Fig. 3. The 3D electrostatic models demonstrate the effectiveness of the field shaping electrode. The field enhancement in MU100 is reduced from 4.96x in the flat electrode topology (left) to just 1.11x in the shielded topology (right).

With use of the field shaping electrodes the average breakdown of scaled MU100 capacitors has been experimentally found to be 117 kV/cm for the 2 cm thick samples - 46% higher than the MU100 capacitors with flat electrodes.

B. *Full Scale Capacitor Design and Assembly*

The requirement for the final assembled capacitor is 130 pF and 500 kV hold off with 50-80% voltage reversal. Rather than build this capacitor as a single set of assembled MU100 capacitors, a modular capacitor was built which can be assembled into the 130 pF capacitor. Each modular capacitor is approximately 16 pF, is rated in unipolar mode for 800 kV and in bipolar mode (ringing operation) for 500 kV operation. The projected lifetime is 10^5-10^6 shots.

It has been shown in prior work with MU100 that small scale capacitor lifetime goes up dramatically when operated at field levels equal to 80% of the average breakdown field [5]. In addition to a 20% derating for long lifetime, the capacitors must be derated by 30-40% to allow for the ringing nature of the applications discharge. Therefore, to achieve a 500 kV, long lifetime capacitor capable of sustained operation under voltage reversal, the device must be able to operate under maximum unipolar pulses of 800kV. This calculation set the target for full scale capacitor design, and 500 kV operation with reversal.

Since scaled capacitors with the field shaping electrode have been shown to have an average breakdown field of 117 kV/cm, the dielectric employed in the full-scale elements will have to be approximately 8 cm thick to allow for 940 kV breakdown voltage or the 800 kV operational voltage. The MU100 substrates produced for the modular capacitors are 2 cm in thickness and four substrates were joined together to achieve the desired dielectric thickness of 8 cm.

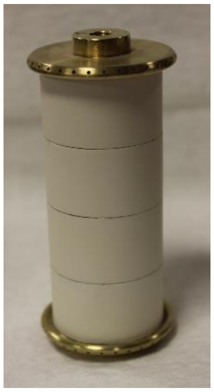

Fig. 4. Advanced assembly methods allow for stacking of dielectric substrates, making assembly of ultrahigh voltage capacitors possible.

Proper stacking of the multiple substrates is crucial to successful full scale device assembly. The dielectric stacks cannot induce any extra field enhancements, meaning the constituent cylindrical dielectric substrates must be stacked concentrically, and there must be a solid equipotential layer between each substrate. In assembly tests, it was found that conductive epoxy was too hard to contain and was not conductive enough through the bulk to be employed in this fashion. Thus, an advanced brazing technique was developed to join the substrates. A eutectic solder was employed as the brazing material which provided exceptional conductivity as well as remaining soft enough to account for variations in material's coefficients of thermal expansion.

C. Encapsulation

Successful design and assembly of the ultrahigh voltage dielectric stacks (which can be tailored to any desired voltage level through varying MU100 substrate thickness and number stacked) was achieved using encapsulation. Encapsulation provided stability to the assemblies, as well as reduction of the possibility for mechanical shock damaging a solder connection. Consequently, the ultrahigh voltage capacitor elements were encapsulated in a very high dielectric strength epoxy increasing its mechanical strength [17]. The encapsulant selected had previously been demonstrated to withstand sufficiently high electric fields and be mechanically robust.

Fig. 5. An encapsulated 500 kV capacitor prototype is shown next to a 500 kV assembly of TDK door knob capacitors along with a ruler for size reference. The capacitor development effort has resulted in 500 kV capacitors that fit in the palm of the hand.

The encapsulant ensures no carbon build up occurs between electrodes over the course of many shots while adding mechanical and thermal stability to the entire device. As shown in Fig. 6, the temperature stability has been measured from 0-40°C for the encapsulated MU100 assembly. The temperature coefficient is low and has been measured over this range at +/- 5%.

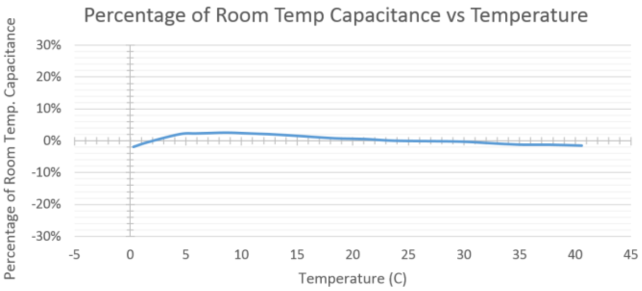

Fig. 6. Temperature stability of encapsulated MU100 material from 0-40 C is +/- 5%.

IV. TEST AND EVALUATION

As shown in Fig. 7, 250 kV capacitors comprised of two brazed sub-elements were assembled to evaluate lifetime. Existing test stands allowed for lifetime to be evaluated at half of the intended operational voltage (250 kV) which necessitated test samples to be fabricated and assembled at half the thickness (2 each, MU100 substrates). Additionally, the lifetime tests were done with unencapsulated devices.

The lifetime testing was done on a test stand capable of 100 ns risetime peak pulses of 250-265 kV and capable of rep rate operation at about 1 pps. The tested device withstood over 10^4 pulses and is undergoing continued testing in Diala AX oil only. The initial lifetime tests are promising for the corresponding 4 substrate capacitors and indicate that they will reliably operate at 500 kV when assembled into the 130 pF capacitor.

Fig. 7. Implementation of the scaling methods described herein have resulted in a device which has withstood 13,000 pulses of 250-265 kV, without encapsulation. The tested device shows promise for a corresponding 500 kV device with twice the thickness and encapsulation.

Additionally, the material has a temperature response not available in film or ceramic capacitors. Ongoing investigations will fully characterize the material from -40°C up to +100°C. The nanodielectrics have excellent frequency response as well as excellent voltage coefficients suggesting that they are a candidate for high voltage, high frequency capacitors.

ACKNOWLEDGEMENTS

The authors would like to thank the generous and continued support of the Joint Non-Lethal Weapons Directorate (JNLWD) and the Naval Surface Warfare Center Dahlgren Division (NSWCDD) for funding this program. Without the funding and support of JNLWD and NSWCDD work like this would not be possible.

REFERENCES

[1] K. A. O'Connor and R. D. Curry, "High dielectric constant composites for high power antennas," in *2011 IEEE Pulsed Power Conference*, 2011, pp. 212-217.

[2] K. A. O'Connor and R. D. Curry, "Recent results in the development of composites for high energy density capacitors," in *2014 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2014, pp. 496-499.

[3] K. A. O'Connor and R. D. Curry, "Dielectric studies in the development of high energy density pulsed power capacitors," in *2013 19th IEEE Pulsed Power Conference (PPC)*, 2013, pp. 1-6.

[4] N. Kallas, R. D. Curry, A. Howard, and K. A. O'Connor, "Characterization of High Energy Density Composite-Based Capacitors Under Pulsed Conditions," in *Proceedings of the 20th IEEE International Pulsed Power Conference*, Austin, TX, 2015.

[5] R. Curry, S. Dickerson, A. Howard, B. Lamb, and S. Mounter, “Scaled DC lifetime, test and evaluation of advanced nanocomposite materials for compact high voltage capacitors,” *2017 IEEE 21st International Conference on Pulsed Power (PPC)*, 2017.

[6] J. J. O’Dwyer, The Theory of Electrical Conduction and Breakdown in Solid Dielectrics. Clarendon: Oxford Press, 1973.

[7] R. Gerson and T. C. Marshall, “Dielectric Breakdown of Porous Ceramics,” *Journal of Applied Physics*, vol. 30, no. 11, pp. 1650–1653, Nov. 1959.

[8] H. K. Kim and F. G. Shi, “Thickness Dependent Dielectric Strength of a Low-Permittivity Dielectric Film,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 8, no. 2, pp. 248–252, Apr. 2001.

[9] S. Cygan and J. Laghari, “Dependence of the Electric Strength on Thickness Area and Volume of Polypropylene,” IEEE Transactions on Electrical Insulation, vol. EI-22, no. 6, pp. 835–837, Dec. 1987.

[10] T. Hayashi, N. Oji, and H. Maiwa, “Film Thickness Dependence of Dielectric Properties of BaTiO3 Thin Films Prepared by Sol-Gel Method,” Journal of Applied Physics, vol. 33, pp. 5277–5280, Sep. 1994.

[11] A. D. Milliken, A. J. Bell, and J. F. Scott, “Dependence of Breakdown Field on Dielectric (interelectrode) Thickness in Base-Metal Electrode Multilayer Capacitors,” *Applied Physics Letters*, vol. 90, no. 11, Mar. 2007.

[12] G. Chen, J. Zhao, S. Li, and L. Zhong, “Origin of Thickness Dependent DC Electrical Breakdown in Dielectrics,” *Applied Physics Letters*, vol. 100, no. 22, May 2012.

[13] C. Neusel, H. Jelitto, D. Schmidt, R. Janssen, F. Felten, and G. A. Schneider, “Thickness-Dependence of the Breakdown Strength: Analysis of the Dielectric and Mechanical Failure,” *Journal of the European Ceramic Society*, vol. 35, pp. 113-123, Sep. 2014.

[14] G. Chen, C. Zhou, S. Li, and L. Zhong, “Space charge and its role in electric breakdown of solid insulation,” *2016 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2016.

[15] D. B. Hopkins, “Design Considerations and Data for Gas-Insulated High Voltage Structures,” *6th Symposium on Engineering Problems of Fusion Research*, Nov. 1975.

[16] A. Bouwers and P. G. Cath, “The Maximum Electrical Field Strength for Several Simple Electrode Configurations,” *Philips Technical Review*, vol. 6, no. 9, pp. 270–278, Sep. 1941.

[17] M. Mayes, J. Mayes, M. Lara, and L. Altgilbers, “High Voltage Properties of Insulating Materials Measured in the Ultra Wideband,” *2005 IEEE Pulsed Power Conference*, 2005.