REPETITIVE PULSE APPLICATION OF SELF-HEALING HIGH VOLTAGE CAPACITORS

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Abstract

In the last fifteen years, self-healing high voltage capacitors have become standard technology for single-shot and low repetition rate (< 1 shot/minute) applications in R&D environments, such as inertial confinement fusion, electromagnetic launchers, electrochemical guns, high field magnet facilities, etc. Such capacitors offer higher energy density and/or longer life and higher reliability in many applications.

Standard self-healing capacitors, built with vapor-deposited metallized electrodes, have limited ability to carry both peak pulse and continuous RMS (root mean square) currents, generate more heat than discrete foil capacitors, and have lower thermal conductivity for heat dissipation. For these reasons, many pulse power applications have been unable to utilize self-healing technology.

For example, moderate to high repetition rate (≥10 Hz), high voltage capacitors built today are generally not of the self-healing type due to the higher energy losses and poorer thermal conductivity of metallized electrode capacitors. This results in large thermal gradients and overheating. Instead, such capacitors are still manufactured using discrete foil electrodes, which provide excellent electrical and thermal conductivity.

The economic and technical benefits of self-healing capacitors continue to drive research and development to expand their operational envelope. Areas of research include "hybrid" electrode systems, integrated cooling, segmented electrodes, and higher temperature dielectrics.

This paper will explore the application of self-healing capacitor technologies to repetitive pulse power systems. Present status of the technology will be described and future performance improvements will be projected.

I. DISCRETE FOIL ELECTRODES

A. Film Capacitor Structures

This paper primarily focuses on wound film capacitor structures used for large energy storage, pulse discharge applications. Other manufacturing techniques, such as flat-stack or monolithic constructions generally utilize the same dielectric and electrode materials, and are therefore subject to the same capabilities and limitations.

A typical extended foil capacitor dielectric/electrode structure is shown in schematic cross-section in Figure 1. Such a stack of layers is wound onto a permanent core or removable arbor to form a capacitor winding. The foil electrodes are typically 4-12 um-thick aluminum foils. The dielectric layers are typically 5-20 um-thick Kraft cellulose paper, polypropylene, or polyester film. Termination of the foil electrodes is by soldering, "schooping" (e.g. arc spray or flame spray), or other techniques on the right and left edges of the structure.

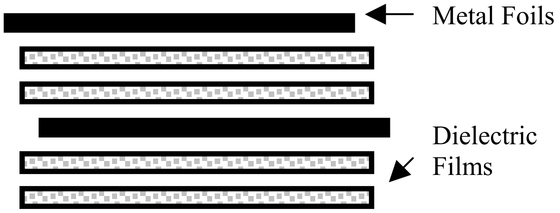

Figure 1. Cross-section of a typical extended foil capacitor structure.

Multiple series capacitances can also be incorporated within a single winding as shown in Figure 2. Here, two capacitances are connected in series. Note the internal margin separating the extended foils. As the number of internal series capacitances is increased within a given total winding width the fraction of volume actually storing energy rapidly decreases due to the internal margins. In addition, the width of the overlap of two foils that form a capacitance becomes smaller, and the required precision in alignment of the foils becomes more critical. (Misalignment will result in capacitance variation between the series capacitances, which results in variation of the voltage appearing across each capacitance when voltage is applied at the terminals. This will reduce capacitor life, as described by Boicourt in [1].)

Figure 2. Two series capacitance extended foil capacitor winding structure.

Note that foil electrodes such as depicted in Figures 1 and 2 do not permit self-healing. When dielectric breakdown occurs the first time, a permanent short-circuit is formed. This severely limits energy density, life, and reliability.

B. Heating in Film Capacitors

In repetitively-pulsed or high frequency AC applications where significant RMS currents flow through capacitors, the design must consider the hot spot temperature rise within the capacitor due to its internal energy losses. Principally these losses consist of ohmic losses in the metallic conductors and frequency-dependant dielectric losses.

The dielectric losses are a function of the basic materials used and their physical arrangement between the electrodes. Once the dielectric structure is selected, the dielectric losses are well defined. (It should be noted, however, that incomplete drying or contamination of the liquid impregnant with ionic species could significantly increase dielectric losses at low frequencies.) Dielectric losses can be quite small in non-polar materials such as polypropylene, which has a dissipation factor of order 0.0001 over a wide range of frequency and temperature. Laminates of polypropylene with Kraft paper have dissipation factors of order 0.001 over a useful range of application conditions. Higher permittivity polymer materials used to achieve higher energy densities in low average power applications, such as polyester (PET), tend to have higher dissipation factors. The ferroelectric polymer PVDF, used in the highest energy density commercial film capacitors, has energy efficiencies of 60 to 80 % at operating electric fields of 350-400 V/um.

Conductor losses can be reduced by using narrower winding materials to shorten the conduction path length, and longer windings to increase the area of the conductor parallel to the current flow, to achieve the same total area and, therefore, capacitance. In discrete foil capacitors, thicker foils or multiple foils per electrode may also be employed to reduce ohmic resistance.

C. Heat Conduction

In any case, there will always be energy losses and heat generation in capacitors. In well-designed capacitors, most of the heat is generated uniformly within the active volume of the winding, that portion of the dielectric actually storing energy, and the adjacent electrodes. The “hot spot” or local maximum temperature rise is the result of this heating and the limited thermal conduction from the core of this region to the external surface of the component. Because of the temperature limitations of organic dielectrics and the acceleration of dielectric aging with increasing temperature, designers typically design long-life capacitors to have maximum hot spot temperature rise values of order 10 °C.

Dielectrics are usually both excellent electrical and thermal insulators, with a few exceptions. The thermal conductivity of polypropylene, for example, is 0.17 W/m/°K compared to 222 W/m/°K for aluminum. Discrete metal foil electrodes provide excellent heat conduction from the hot spot within a capacitor winding to the extended and terminated edges, with a few tens of microns separating any part of the active dielectric from a foil.

Note that the same changes in geometry that tend to reduce conductor losses also tend to reduce the length of thermal conduction paths, and are therefore doubly beneficial. Narrow width winding materials, producing discoidal or annular winding geometries, or flattened winding versions resembling thin rectangular slabs, are most effective in high repetition rate pulse applications.

In some of the highest average power capacitors, such as those used in induction heating applications, extended foils are soldered directly to pipes through which a liquid coolant is flowed. However, such measures can add significantly to the total weight and volume required for a system.

II. SELF-HEALING ELECTRODES

A. Advantages

Self-healing metallized paper capacitors were introduced in Germany in the 1940’s. The foil electrodes of Figure 1 and 2 are replaced with vapor-deposited metallization directly on the dielectric substrate. Typically the metal is aluminum, zinc, or an alloy, and the thickness of the layer is a few hundred Angstroms. The termination is almost always done by schooping (molten metal spraying process).

This technology not only eliminates the volume of the aluminum foil electrodes, but also permits the self-healing process to occur. Self-healing capacitors can sustain many dielectric breakdowns during their operating lifetime, allowing much higher design values of electric field, and therefore higher energy densities.

B. Self-Healing Process

When a dielectric breakdown occurs, the high current density in the metallized electrode immediately around the breakdown site will vaporize the metallization. The arc will be quenched and the metal oxidized and re-distributed, so that an insulating region, or “clearing”, is formed around the breakdown site. The substrate material and any surrounding impregnant are involved in the self-healing process, because the local heating will pyrolize some of this material.

Today, metallized film capacitors are commonly made from polypropylene, polyester, PEN, polycarbonate, polyimide, polytetrafluoroethylene, and other plastics. The self-healing characteristics of these capacitors vary greatly. Some plastics do not support reliable self-healing because they carbonize, leaving a semiconducting, rather than insulating, region around the breakdown site.

Another form of self-healing capacitor utilizes metallized electrodes that are segmented, divided into small regions (typically 1-100 cm2) by means of narrow unmetallized gaps, or margins, and connected to one another by means of fusible links. These designs do not rely on the clearing at the breakdown site, but isolate the segment involved in the breakdown by fusing of the links. Such designs must generally be operated at reduced stress levels compared to those that rely on self-healing breakdown sites because of the relatively large electrode area and capacitance lost with each blown fuse link. However, lower resistivity metallizations can be utilized in these designs, reducing their ESR and increasing their RMS current capability. Pulse discharge applications, however, make such designs more difficult, due to the possibility for fuse links to open on high peak current, but still normal, discharges.

In high voltage capacitors made by GAEP, Kraft paper, polypropylene, and polyester are most commonly used for the metallization substrate.

Kraft cellulose paper is generally considered the best substrate for self-healing characteristics, but it is limited to thicknesses of 6 um or greater and must generally be combined with at least one additional layer of dielectric to achieve adequate dielectric performance. For example, single-side metallized paper may be combined with a layer of plastic film to form a structure like that shown in Figure 3.

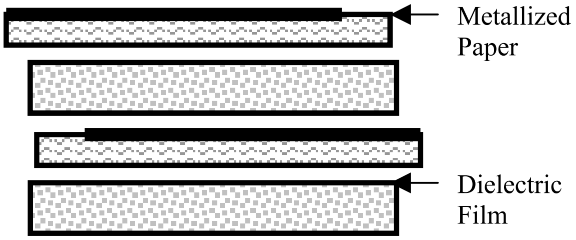

Figure 3. Metallized paper combined with plastic film in a capacitor.

In some cases, the disadvantages of paper as a dielectric, and its advantages as a substrate for self-healing metallized electrodes, result in the use of both-sides metallized paper, sometimes referred to by General Electric's trade name, "Soggy Foil". The elimination of relatively lossy paper from the dielectric and the use of a low-loss polymer such as polypropylene film, results in a capacitor structure that is suitable for 60 Hz AC applications, for example.

C. Heating and Conduction in Metallized Capacitors

In discrete foil electrode capacitors, dielectric losses dominate at frequencies below the megahertz range. In large metallized electrode capacitors, the transition frequency is typically in the kilohertz range, due to the relatively high resistance in the metallization itself, as well as the contact resistance in the termination. The surface resistivity of the metallization, expressed in ohms per square, and the geometry of metallized capacitors are both important in determining their effective resistance and high frequency performance. The use of lower resistivity metallization is limited by the requirements of self-healing. These conflicting requirements have led to the widespread use of segmented electrode patterns with fusible links to achieve a secondary self-healing affect. The use of longer windings of narrower width material is another way to reduce ESR and produce metallized electrode capacitors capable of both fast discharge and carrying higher RMS currents.

Metallized electrodes offer little benefit as heat conductors because of their small thicknesses (~300 Angstroms). Dual-metallized dielectric substrates also offer little in terms of heat conduction, although they do reduce the effective heat energy density (W/cc) in the capacitor volume. Sub-micron thick liquid impregnant layers are ineffective for convecting heat out of the structure. Only discrete metal foils provide effective thermal conductors within capacitor windings. Thus, there is a basic problem in achieving self-healing in high repetition rate pulse or other high RMS current capacitors.

III. HYBRID ELECTRODE DESIGNS

A. Design Approaches

Hybrid electrode capacitors are manufactured with combinations of two different types of electrode in one capacitor structure. These can be combinations of different types of metallized electrodes (Figure 4), or combinations of metallized and discrete foil electrodes (Figure 5).

Figure 4 depicts a design that has been used to increase the peak current capability and "speed" of a relatively low voltage capacitor, in comparison with a simple metallized film design. The extended electrodes are both-sides metallized paper or film, and the floating electrode is a metallized dielectric film.

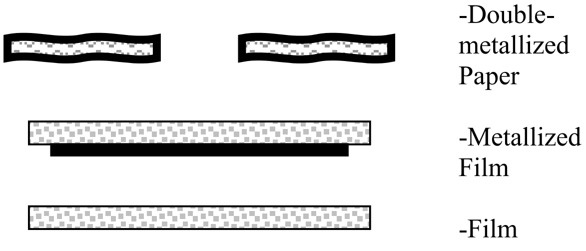

Figure 4. Hybrid design that combines two different types of metallized electrodes.

Hybrid designs consisting of metallized paper, plastic film, and extended aluminum foils have been supplied by GAEP for a number of applications, including rock blasting/hard rock mining, food sterilization, and ICF facilities. In these applications, the hybrid design has mainly been used as a means of economically increasing life and reliability in moderate peak current applications. Hybrid capacitors with stored energies up to 25 kJ and operating voltages up to 22 kV have been delivered.

GAEP's experience with these custom designs provides a basis for designing self-healing hybrid capacitors for higher repetition rate, faster discharge applications. Figure 5 shows an example of how such a hybrid capacitor might be built. In this case, aluminum foils are used for the extended electrodes to provide thermal conduction. The floating electrode is made with both-sides metallized paper or film, to provide high peak current capability. The dielectric would be one or more layers of polypropylene film. Note that the fraction of the winding volume actual storing energy will be about the same or lower than in a conventional foil capacitor design, in which three to six dielectric layers would be typical.

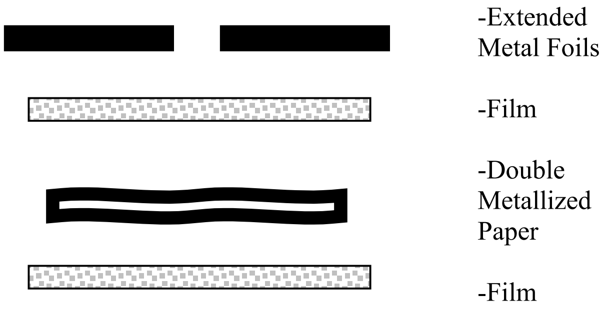

Figure 5. Example hybrid design combining metallized and foil electrodes for higher repetition rate capability.

B. Design Calculation Example

Consider the case where the capacitor manufacturer simply substitutes a floating both-sides metallized paper layer for an aluminum foil in a standard foil capacitor design. The impacts on the characteristics of the capacitor are primarily seen at high frequencies, where the dissipation factor and ESR are substantially increased. Figure 6 depicts the calculated result of such a substitution on the DF of a 1 uF 20 kV GAEP plastic case capacitor with 127mm dielectric width. Note that the thermal conductivity of the winding is reduced by about a factor of two with the substitution, but this has a much smaller effect on the hot spot temperature rise than the increase in dissipated energy. In this example, the foil capacitor was rated at 62 Amps RMS for a 10 °C hot spot temperature rise. The substitution resulted in a predicted temperature rise of 33 °C at 62 Amps RMS, or a reduced current rating of 29 Amps RMS to limit the temperature rise to 10 °C. In contrast, a purely metallized electrode capacitor of the same size was calculated to have an RMS current rating of 12 Amps RMS.

Reducing the dielectric width from 127 to 75mm and compensating for the reduced packing factor by reducing the dielectric thickness by 15% resulted in a 45 Amp RMS rating. The reduction in dielectric thickness was easily justified by the self-healing capability.

Note that the metallization resistivity used in these calculations was chosen to be relatively high to insure adequate self-healing. Further optimization of the metallization to reduce the DF and ESR is feasible.

The hot spot temperature calculations indicated that in both the extended foil and extended foil hybrid designs, the majority of the temperature gradient was at the ambient air to case surface interface. In modeling a metallized film version of the same capacitor, a significant temperature gradient was predicted within the windings. This confirms the benefit of the extended aluminum foils in conducting heat out of the winding, and also indicates that users will be able to operate such capacitors at higher RMS current values if circulated air cooling is provided.

The peak current ratings of the different capacitor designs considered here ranged from 0.3 kA for a purely metallized film design to 66 kA for the standard extended foil construction. The ratings of the 125mm and 75mm extended foil hybrid designs were estimated at 13.8 and 23.8 kA respectively.

The primary benefit of the specific extended foil hybrid capacitor design described here would be in the additional lifetime and reliability afforded by self-healing. In some applications, this benefit would outweigh other technical and economic considerations.

IV. CONCLUSION

Self-healing capacitors offer longer life and higher reliability than discrete foil designs. GAEP has utilized this feature in the design of a number of high energy capacitors for industrial and R&D applications.

In order to achieve self-healing in capacitors designed for high average power, repetitive pulse applications, designs combining extended aluminum foils with floating metallized film or metallized paper electrodes can be utilized. Such designs reduce the ohmic portion of the ESR as well as the thermal gradients when compared to symmetric metallized electrode designs. In addition to these advantages, higher peak current densities can be achieved for faster discharge capability. These attributes make hybrid capacitors a desirable approach for many applications.

V. REFERENCES

[1] G.P. Boicourt, “Distribution of Maximum Voltages in Multisection Capacitor Windings and in Certain Series-Connected Capacitors,” Los Alamos Scientific Laboratory, Los Alamos, NM, Report Number LA-6371, May 1976.

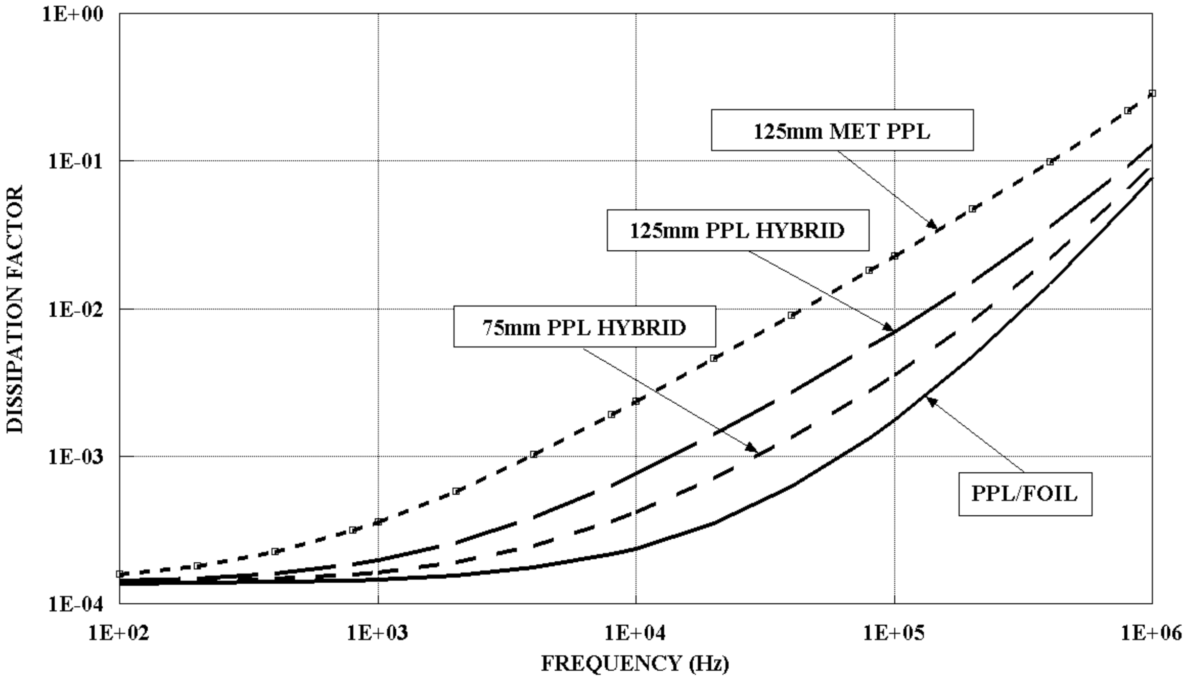

Figure 6. DF versus frequency for a standard 2-series section extended foil design (PPL/FOIL), a metallized film version (125mm MET PPL), and two PPL film hybrid electrode designs using 125mm and 75mm wide material.