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TITLE: ADVANCED DEVELOPMENT OF ELECTRICAL-ENERGY-STORAGE COMPONENTS FOR HIGH-RELIABILITY APPLICATIONS

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ADVANCED DEVELOPMENT OF ELECTRICAL ENERGY STORAGE COMPONENTS FOR HIGH RELIABILITY APPLICATIONS

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Introduction

Evolving power conditioning system requirements in the areas of magnetic confinement fusion, inertial confinement fusion, molecular laser isotope separation, particle beam technology, radar, communications, and medical electronics will place severe demands upon repetitive pulse-power system components. Currently, a principal pacing system component in high reliability repetitive pulse power technology is the energy storage capacitor. Limited resources are being focused on understanding the physical and technological problems associated with extending lifetimes, reliabilities and energy densities of repetitive, high energy density pulse discharge capacitors. Burst mode engineering development efforts in industry have produced highly refined, reliable capacitors for specific applications. The scope of these efforts, however, have not permitted the extensive R&D necessary to generate a comprehensive data base that encompasses the anticipated broad spectrum of operational requirements for continuous duty, repetitively operated pulse discharge capacitors. The present knowledge base on power capacitors consists of recent burst mode data plus a detailed macroscopic engineering data base on the capabilities and limitations of 60-Hz power factor correction and single-shot pulse discharge applications, created over the past 70 years by the capacitor manufacturing industry. Burst mode data from industry[1,2], and multi-kilohertz testing activities at Los Alamos[3] have shown that this highly refined lifetime and reliability data do not necessarily scale to repetitive operation. Development projects may take 2 to 5 years to complete so efforts should begin now to acquire the capabilities necessary for the design and fabrication of the repetitive power capacitors that will be needed in future technologies.

Program Objectives and Structure

A joint program for the research and development of repetitively operated, pulse discharge energy storage capacitors has been initiated at the Los Alamos and Sandia National Laboratories. The purpose of this activity is to create the knowledge base required in the design and fabrication of ultimate performance, materials-limited, multi-kilojoule capacitors that are continuously operable to 100 Hz with lifetimes approaching 10^7-10^8 charge-discharge cycles at 99.99% reliability. The project approach to the development of practical repetitive pulse power capacitors and the acquisition of a complete, detailed, understanding of their characteristics is anticipated to evolve as an interactive and iterative combination of the following project components:

- o initial selection of prototype capacitor designs, based upon the experiences in capacitor design and fabrication at Sandia and in industry;
- o implementation of dc partial discharge experiments contrived to develop an understanding of the mechanisms involved in the degradation of laminar dielectric systems caused by internal partial discharge activity; to identify a correlation between dc partial discharge analysis and repetitive pulse discharge lifetimes so nondestructive test screens can be defined;
- o deployment of extensive repetitive operation life testing experiments and the acquisition of data sufficient to statistically characterize lifetime as a function of electrical stresses, including repetition rate;
- o development of mathematical and physical models from the lifetime data; i.e., the characterization of capacitor life as a function of the pertinent operating stresses and design parameters, including verification of any postulated scaling relations or model extrapolations; and
- o analysis of test results to develop a detailed understanding of the major failure mechanisms so design improvements can be implemented.

Currently, the dominant energy density/lifetime limiting mechanisms in spirally-wound, liquid impregnated, high energy density capacitors are almost certainly a direct result of internal partial discharge phenomena, either in the bulk of the dielectric or at the foil edges. The initial objective of this joint research and development program is to characterize, understand, and eliminate the causes or effects of these partial discharges so other, second order effects can be identified and studied. The activity is structured into five distinct but interactive components:

- o design and fabrication of prototype test capacitors;
- o dc partial discharge analysis;
- o repetitive charge-discharge life testing;
- o theoretical and experimental analysis; and
- o computer modeling.

A brief overview of each of these program elements is presented below.

Capacitor Design and Fabrication

The extensive experience and expertise developed at Sandia in the areas of capacitor design, precision fabrication, and theoretical/experimental analysis complements and reinforces the testing and analysis capabilities at Los Alamos. Sandia has developed a highly refined spirally-wound capacitor fabrication technology that includes ultra-precision, dust-free winding machinery; high purity, rigorous vacuum impregnation processes; and unique capacitor designs and construction techniques. This facility is capable of producing near materials-limited, precision-fabricated, experimental-grade prototype capacitors in a wide variety of design configurations and sizes for test and evaluation.

Repetitive Charge-Discharge Life Testing

A 300-kW, 1-kHz capacitor modulator is under construction at Los Alamos and is scheduled to become operational in 1982. The modulator is designed for millisecond resonant command charge, 100ns critically damped RC command discharge, and is configured to test several prototype capacitors simultaneously. The facility will be equipped with extensive diagnostics so all electrical and environmental stress parameters can be accurately measured and an impending end of life of a sample can be detected prior to catastrophic failure.[4]

DC Partial Discharge Analysis

A high performance dc partial discharge analyzer (PDA) system has been acquired from the James G. Biddle Company. The system consists of a low noise, high voltage dc power supply, a very sensitive partial discharge detector and display coupled to a versatile multi-channel analyzer with diskette storage and computer I/O capabilities. Ultimate detection sensitivity

of the PDA system is better than 0.05 pC. The PDA is being used to quantitively determine the corona inception characteristics of elementary foil-edge configurations in high purity, degasified liquid impregnants. In addition, pulse height analysis (counts vs pC) and multichannel scaling (counts vs time) of the partial discharge activity in prototype capacitors are being recorded prior to life testing. Correlation trials will be attempted between these data and the lifetimes exhibited during repetitive, charge-discharge testing.

Theoretical Analysis

Mechanisms that account for significant lifetime and performance degradation will be identified, analyzed and understood so their causes or effects can be eliminated. This may involve several disciplines in the physical and engineering sciences. The technical resources of a national laboratory environment can be efficiently matrixed so the state-of-the-art in any scientific discipline can be quickly focused on a theoretical or developmental problem area.

Computer Modeling

Modeling of the electric field at the foil edges and in the margins of elementary, spirally-wound capacitor structures is underway. These models are computer generated by numerically solving the 2-dimensional Laplacian over regions of interest and describe various foil-edge shapes, dielectrics and impregnants. Recent foil-edge partial discharge experiments have indicated that space charge considerations near the foil edges must be included in these models; efforts are currently in progress to understand this mechanism so more appropriate models can be synthesized.

Prototype Capacitor Design

Analysis and refinement of the performance of conventional, liquid-impregnated, spirally-wound plastic film and foil configurations will be undertaken. These efforts will initially be concentrated on eliminating the effects or causes of internal partial discharges. Refinements in design and fabrication over conventional, industrial methods are anticipated to be in the areas of:

- o optimum materials for the dielectric and impregnant;
- o ultra-precision, wrinkle-free, controlled-tension winding;
- o high purity, rigorous vacuum impregnation;
- o highly reliable electroding process for internal connections;
- o expansion bellows compensation of temperature-induced impregnant volume changes;
- o foil/dielectric thickness ratio; and
- o foil-edge electric field reduction.

Extended-foil configurations will be used exclusively because heat can be extracted from the interior of the winding much more efficiently than with tab-insert connections. Also, tabs cannot support the high i^2t of pulse-discharge operation without sustaining arcing damage at the contact points on the buried foils. Floating foils will not be used, primarily because these foils have no heat-sinking capabilities.

Partial Discharge Mechanisms

Two types of partial discharge (PD) activity can be present in conventional energy storage dielectric systems. One type occurs in or between the layers of dielectric between the plane surfaces of the foils; the other occurs at the buried foil edges which define the inner boundary of a margin. If these phenomena incept, the integrity of the dielectric is degraded and the lifetime of the capacitor is reduced.

Bulk-Dielectric Partial Discharges.

This may be the most critical of the two PD phenomena because it occurs in regions difficult to impregnate and has been observed to cause bulk-dielectric punch-through prior to foil-edge PD failure, even though occurrence is in a region of relatively low electric field stress compared to the foil edges. Present qualitative experiments on voltage punch-through of liquid-impregnated plastic film dielectrics have demonstrated that bulk-dielectric PD activity increases from essentially zero to very high count rates and magnitudes in a time frame of 0.1 to 1 s prior to failure. The probable causes are of bulk-dielectric PD are:

- o inadequate impregnation allowing dry, gaseous inclusions to remain in the regions between the foils;
- o trappped voids, open voids, inclusions and anomalous inhomogeneities in the solid dielectric;
- o cavitation of the liquid impregnant by electromechanical shock in the dielectric during pulse discharge (or pulse charge);
- o inadequate degasification of the liquid impregnant allowing adsorbed gasses and moisture to condense out of solution; and
- o loose particulates trapped in the layers of the winding during fabrication.

Low permittivity inhomogeneities in the dielectric regions cause localized electric field enhancement that results in PD inception. These rf plasma relaxation oscillations[4] may or may not be immediately self-quenching; however, small amounts of PD activity can cause localized pyrolysis and generate uv radiation, which chemically degrade the dielectric in the immediate volume region. These effects enhance the conditions for continuing PD by creating gaseous and solid by-products with low breakdown voltages, low permittivity or lossy, unstable dielectric properties.

Foil-Edge Partial Discharges

A sharp and irregular foil edge defines the inner boundary of a margin. The electric field at these buried foil edges can be quite high, especially for unaligned foils, depending on the effective foil-edge radius and the dielectric thickness, assuming wide margins (>0.1 in.).[5] DC partial discharge experiments have been performed on elementary foil-edge structures in an attempt to understand the fundamental processes involved in this phenomenon. For liquid-impregnated, laminar plastic film and laminar, dry mica dielectrics, the intensity (counts/time, and counts/pC) of the PD activity at the foil edge is greatest during the charge and discharge periods, i.e., is $\dot{V}$ dependent, where V is the voltage between adjacent foils. It is hypothesized that charge is distributed from the foil edge onto the dielectric surfaces in the margin, or into the volume regions in the margin, during the period $\dot{V} > 0$. While $\dot{V} = 0$ and $V > 0$, there is little PD activity. A redistribution of charge occurs near the foil edge such that an equilibrium condition is reached where the electric field intensity at the foil edge is reduced below the PD inception threshold. When $\dot{V} < 0$, the charges are again dynamic because equilibrium is disturbed and PD activity increases significantly. The greater the magnitude of $|\dot{V}|$, the higher the PD intensity. The exact relationship of this dependency has not yet been determined. Experimental data showing this result is depicted in Fig. 1 for a single foil edge (1.0-in. length) adjacent to a ground plane, separated by 0.002-in. plastic film and impregnated under vacuum with degassed mineral-base transformer oil. A dry mica capacitor was found to exhibit the same result, although the PD activity was significantly higher. This is shown in Fig. 2.

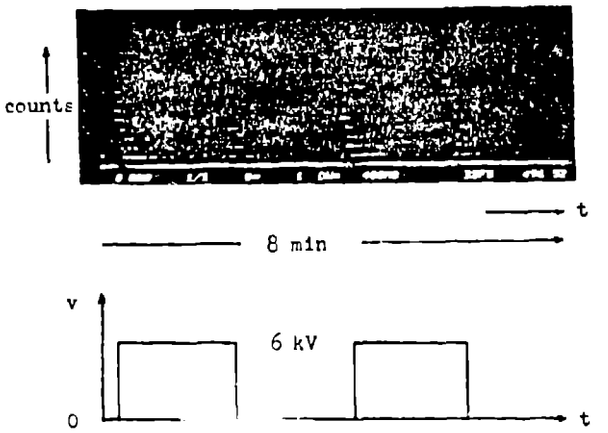

Fig. 1. Partial discharge counts vs time for a 1-in. foil edge as a function of applied voltage.

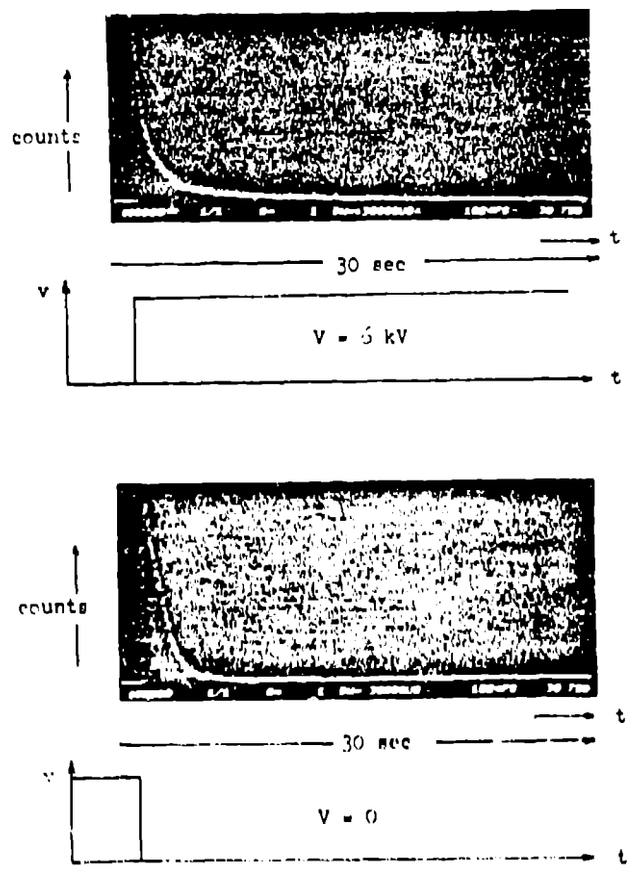

Fig. 2. Partial discharge counts vs time for a dry-mica capacitor as a function of applied voltage.

Sandia Capacitor Fabrication Technology

A highly refined, advanced technology for the fabrication of spirally-wound, plastic film, liquid-impregnated, high energy density capacitors has been developed over the past several years.[7] These advances are a direct spin-off from successful programmatic efforts to create reliable (>9,952) high energy density single-shot capacitors with unusually long shelf lives. See Fig. 3.

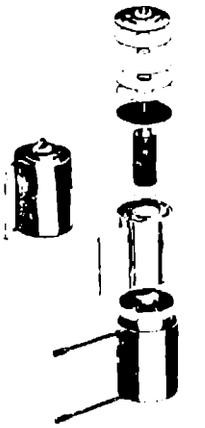

Fig. 3. Sandia capacitor assembly.

Ultra-Precision, Controlled Tension Winder

This machine (Fig. 4) has the capability to wind multilayer turns of rollable dielectric and foil onto a spool such that each layer has a wander tolerance of less than 0.005 in. Precision instrument bearings are used on all rollers and the position of each layer as it is fed onto the capacitor spool is controlled by precise mechanical alignment. The tension of each layer is controlled by electric motor torque applied to the feed rollers. An auxiliary stainless steel roller applies a force to each layer orthogonal to the feed direction and calibrated force transducers on these rollers continuously monitor the winding tension. The metallic surfaces of these auxiliary rollers assist in dissipating electrostatic charge that would otherwise interfere with the precision with which each layer can be located on the capacitor spool. Film or foil layers do not slide over felt positioners, as is common practice in commercial winders, so no felt particles are wound into the dielectric system. The winding operation is performed in a positive pressure, clean-room environment and dust particle contamination is reduced to an absolute minimum. It has been discovered that a relatively loose, controlled tension during the winding operation significantly increases the mean discharge life of impregnated windings, and that the spread in the breakdown voltage from winding to winding is reduced. The reduced winding tension facilitates the vacuum impregnation process because gaseous inclusions between layers are more easily displaced by the liquid impregnant.

Electroding Process

A unique method for making electrical connections to the extended-foil edges of a winding has been shown to significantly increase the mechanical and electrical integrity of this difficult fabrication problem. A copper screen is cut to the same diameter as the winding and placed flat against one of the surfaces formed by an extended-foil edge. A special silver-filled, high viscosity epoxy is mortised over the screen to a thickness of 0.1 in.; the paste penetrates the screen and adheres to the extended-foil-edge surface. The viscosity of the epoxy prevents further penetration into the winding. Small slots are maintained through the epoxy layer to facilitate vacuum impregnation of the winding, and a threaded brass fixture, part of the copper screen, allows the individual windings to be screwed together to form reliable series connections.

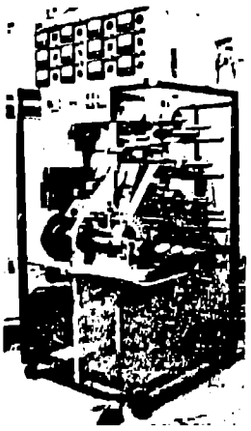

Fig. 4. Sandia precision winding machine.

Vacuum Impregnation Process

Impregnation is a critical process in the fabrication of reliable, high energy density capacitors. It is essential that all gases and moisture trapped in the winding layers be eliminated and displaced by the liquid impregnant; otherwise a gaseous inclusion or a dry spot becomes a site for partial discharge inception that can lead to rapid failure. The exclusive use of plastic film as the dielectric material aggrevates the impregnation problem because films tend to cling together, similar to plastic food wrap. Kraft paper, the standard dielectric used in oil-filled capacitors prior to the availability of quality plastic films, acts as a wick for the impregnating fluid because of the porous, fibrous nature of paper materials. Paper, however, is an inherently low energy density dielectric, and can be easily over-dried under vacuum resulting in brittleness and cracking. Films can be evacuated, prior to impregnation, at pressures far below the limit for paper for indefinite periods of time.

There are four major steps in the Sandia vacuum impregnation cycle:

1. evacuation of the capacitor case containing the windings to scavenge any volatile substances and to remove as much of the trapped and free gases as possible; this is done at 10^{-4} Torr for 24 h;
2. thin-film degasification of the impregnant at a vacuum slightly above its vapor pressure to remove all free and adsorbed gases and moisture, and filtering to remove all particulates; for perfluorocarbons, this pressure range is 3 to 30 Torr and the operation requires 24 h; filtering is accomplished during degasification using a 2μm borosilicate filter;
3. filling of the capacitor with impregnant at the liquid vapor pressure and maintaining this pressure for 24 h; and
4. sealing of the completely filled case at a positive internal pressure of 47 psia.

Perfluorocarbons as Dielectric Impregnants

Perfluorocarbons are available in many grades that cover a wide spectrum of physical properties. Several of these perfluorocarbon grades have a combination of unique properties that makes them ideal for impregnating fluids.[5] Salient properties of perfluorocarbons as liquid impregnants include:

- o chemical inertness, hence compatibility with other materials; no degradation due to chemical reactions such as oxidation;
- o very low viscosity and interfacial tension that facilitates impregnation and degasification;
- o very high thin-film voltage breakdown strength;
- o very low dielectric losses, even at high frequencies;
- o high heat of vaporization and low boiling temperature that inhibit and quench partial discharge inception and pyrolysis; and
- o low hydroscopic activity.

Because of the low dielectric loss and high voltage breakdown strength of perfluorocarbons, this component of a dielectric system can be stressed by much higher electric fields than conventional impregnation fluids. The relative dielectric constant (ϵ_r) of perfluorocarbons is 1.7 - 2.0; for most plastics, $\epsilon r > 2.0$. For a plastic film/perfluorocarbon composite, the electric field tends to be higher in the fluid than in the solid. Because high purity, degassed perfluorocarbons strongly inhibit and quench PD activity and, in thin films, exhibit voltage breakdown strengths greater than plastics, the degrading effects caused by open voids in plastic film are nullified in the presence of these fluids.

Expansion Bellows Control of Case Pressure

Perfluorocarbon fluids have relatively large temperature coefficients of expansion. To prevent temperature-induced, high internal pressures that rupture the completely filled and sealed case, a thin-metal bellows is inserted in the axial hole through the center of the windings. Prior to the sealing processes, the bellows is compressed to one-half of its length at STP by pressuring the liquid impregnant. The case is then sealed by crimping and ultrasonic welding of the filler tube. After sealing, the bellows prevents hydrostatic lock, maintains a positive internal case pressure (47 psia) that effects a continuous, long-term impregnation of the windings, and prevents de-impregnation caused by mechanical forces associated with repeated charge-discharge cycling.

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