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TITLE: PARTIAL DISCHARGE CHARACTERISTICS OF LIQUID-IMPREGNATED LAMINATE DIELECTRIC STRUCTURES

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ABSTRACT

Foil-edge partial discharge phenomena in high energy density, spirally-wound capacitors have been investigated. A partial discharge dependency on $\dot{V}$ has been found to exist in liquid-impregnated, laminar plastic film dielectric structures. Experiments support the hypothesis that electric charges are injected into the dielectric regions near the foil edge by field-controlled charge injection during impressed voltage transients. The resulting conduction current space charge can establish equilibrium by reduction of the electric field intensity below the partial discharge inception threshold. A temporal characterization of this space charge injection is discussed relative to the effect on partial discharge inception at the foil edge.

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INTRODUCTION

Evolving power conditioning system requirements in many important technological areas will place severe demands upon repetitive pulse-power components. A principal pacing system component in high reliability, repetitive pulse-power technology is the energy storage capacitor. 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 ongoing activity is to create the knowledge base necessary for the design and fabrication of materials-limited, multikilojoule capacitors that are continuously operable to 100 pps with lifetimes approaching 10^9 charge-discharge cycles at 99.99% reliability. Recently increasing availabilities of quality plastic films, especially polypropylene, and the discovery of the excellent properties of perfluorocarbon liquids for impregnation fluids (1) make spirally-wound, plastic film/liquid impregnated capacitors the leading candidate for high energy density, repetitively operated pulse discharge energy storage devices. The dominant lifetime-limiting mechanism in this type of high energy density capacitor is a direct result of partial discharge activity at the buried foil edges, where the electric field is maximum. An initial objective of this joint program is to characterize and understand the mechanisms of this partial discharge phenomenon.

FOIL-EDGE ELECTRIC FIELDS

A sharp and microscopically irregular foil edge defines the inner boundary of a capacitor margin. The electric field intensity at these buried foil edges can be very high, especially for unaligned foils, a configuration that exists in all real capacitor geometries. Extended-foil designs, because of inherently better inductive, peak current and heat-sinking characteristics, will be considered as the model for discussion. Figure 1 is a cross-sectional view of a hypothetical foil edge, the section taken parallel to the axis of the capacitor winding. This model (2) embodies only the effects of field enhancement caused by the dielectric permittivities interacting with the geometries of the dielectric and foil edge; intrinsic, extrinsic and charge-injection conductivities have been ignored. The permittivities are assumed to be homogeneous and of an electronic and/or ionic nature (no rotational orientation polarization), so no frequency dependence in the permittivities exists below microwave frequencies. Under these assumptions, the electric field intensities at the foil-edge surfaces of Fig. 1 are representative of the behavior during the risetime of a fast voltage transient impressed on the foils. Although the particular foil-edge shape is arbitrary but conservative relative to real foil edges formed by commercial shearing processes, the tendency of field enhancement can be seen to be extreme. An enhancement factor of slightly greater than 7 occurs at the locus where the foil-edge radius is minimum (0.01 mil); hence for this shape a field of 7800 volts per mil per kilovolt is hypothesized during a voltage transient. For extremely well degasified and filtered perfluorocarbons, the thin-film breakdown strength has been measured to be in the range 11 kV - 13 kV per mil. As shown in Fig. 1, for an impressed transient voltage less than 2 kV, the breakdown threshold of the liquid impregnant is exceeded and partial discharges occur characteristically in the form of low intensity (< 20 pC) impulse streamers at the foil edge.

PARTIAL DISCHARGE INCEPTION VS DIELECTRIC CONDUCTIVITY

Considering only the effects of the dielectric permittivities and conductivities interacting in a laminar capacitor geometry of large area and small thickness, a two-component dielectric system can be modeled as shown in Fig. 2. The value of the ratio permittivity/conductivity is on the order of minutes for polypropylene and perfluorocarbons (10^{-11} F m^{-1}/$10^{-15}\Omega^{-1}$ m^{-1}) such that the effect of the dielectric conductivities on the electric field intensities is negligible for angular frequencies exceeding fractional radians per second. The model shown in Fig. 1 is therefore appropriate for describing the electric field at the surfaces of the foil edges when considering only the contributions from dielectric permittivity and conductivity. The breakdown threshold of the impregnant at the locus of maximum electric field intensity is again theoretically exceeded by voltages less than 2 kV with rise-times approaching dc values.

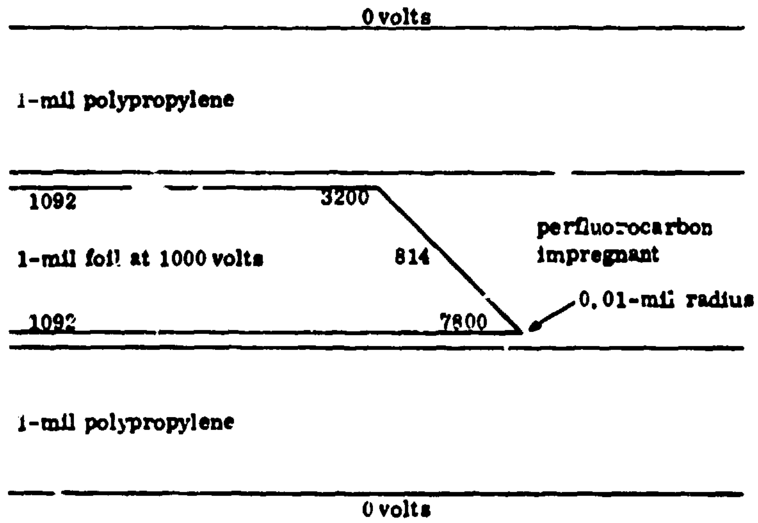

Fig. 1. Electric field strength in volts per mil at foil-edge surface for 1000 volts applied to capacitor winding.

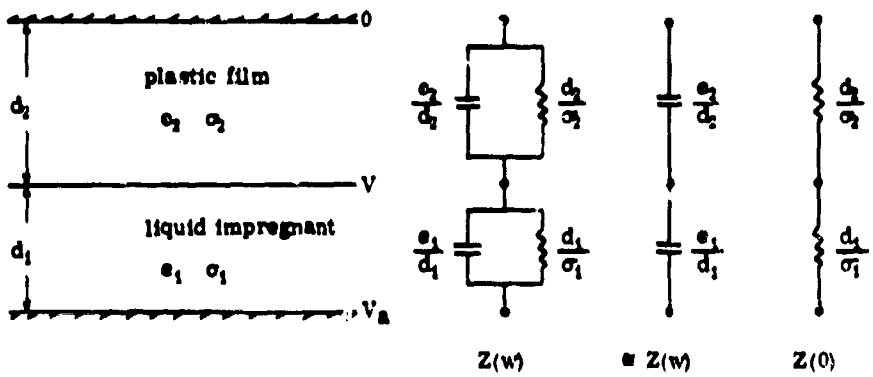

Fig. 2. Two-component dielectric system - impedances vs angular frequency.

PARTIAL DISCHARGE INCEPTION VS INJECTED SPACE CHARGE

Charge carriers under the influence of an electric field can be injected into a dielectric material from the surface of an electrode. These carriers are transported through the dielectric and are captured at the opposing electrode. Charge injection is not an impulse breakdown process like partial discharges, but is a continuous conduction phenomenon similar to intrinsic or extrinsic conduction except the origin of the carriers is entirely external to the dielectric, and the current is hyperlinear with the electric field. Two types of injection processes that have been specifically identified and described are Schottky and tunnel injections (3). Regardless of the physics at the electrode/dielectric interface, the result is a current density in the dielectric that can approach a space charge limited condition, where the electric field at the injection site is reduced to a small value by the proximity of the space charge. Because charge injection is a field-controlled process, the current density will be maximum at the high field sites on the foil edges. The conduction path follows the electric field vector and injected current flows from a foil edge to the opposing foils through the multiple layers of the dielectric, a distance approximating 1 mil. If the charge injection process can become established during the rise or fall times of voltage transients across the foils, the reduction of the electric field at the foil edge would increase the partial discharge inception voltage. Although the time constants for the distributing of space charge during field-controlled injection are significantly shorter than the ϵ/σ ratio discussed above, the values are large compared to the millisecond charge times and nanosecond discharge times of pulse discharge capacitor service.

Using the transport time for a slow electron under the influence of a 1-kV per mil field to travel a distance of 1 mil as a measure of the injected space charge formation time,

$$t_f = \frac{d}{E\,u} \quad ,$$

where u is the effective carrier mobility, d is the dielectric thickness, E is the electric field near the foil edge (spatial average), and t_f is an estimate of the space charge formation time. The mobility is known to be in the range 10^{-12} - 10^{-6} $m^2\ V^{-1}\ s^{-1}$ for most dielectrics (3) and is relatively low because the carriers spend most of the time in shallow traps so the mobility is an effective value (3,4). The range of t_f is then calculated to be $6 \times 10^{-7} < t_f < 6 \times 10^{-1}$ s.

The hypothesis that space charge associated with field-controlled injection reduces the electric field intensity at the high field sites on the foil edges and hence increases the partial discharge inception voltage has been supported by laboratory experiments, which are summarized in Figs. 3 and 4.

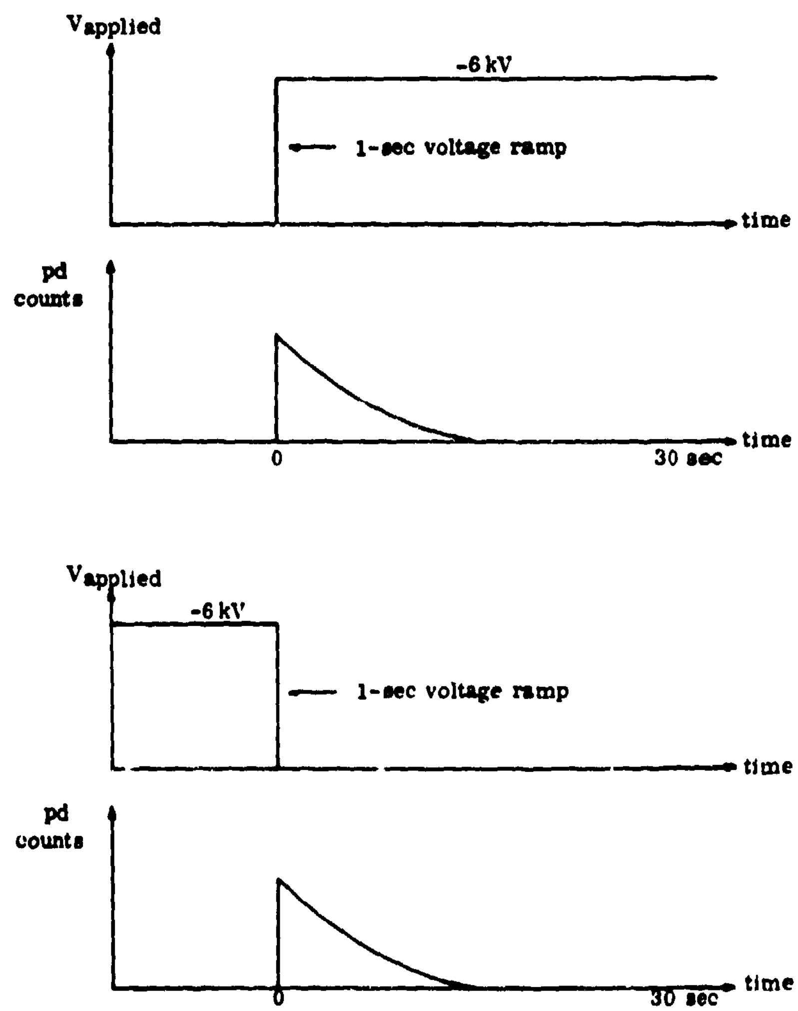

Fig. 3. Partial discharges at foil-edge structure vs time as a function of applied voltage.

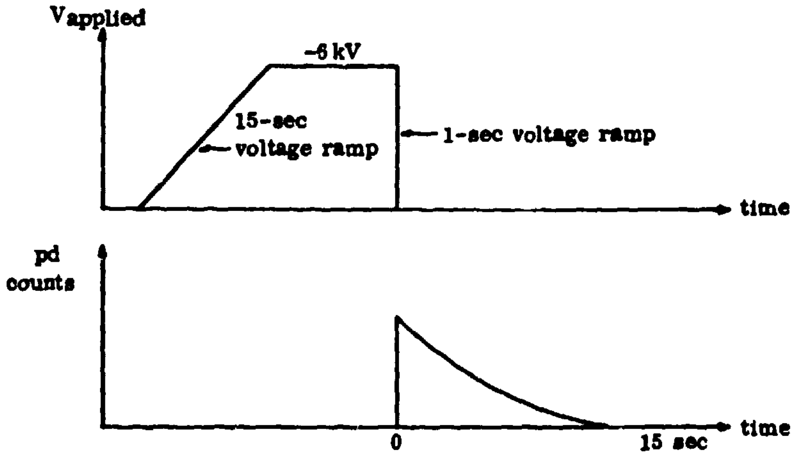

Fig. 4. Partial discharge at foil-edge structure vs time as a function of applied voltage; risetime below $\dot{V}$ threshold.

Mock-ups of laminar foil-edge structures were constructed using 1-mil mylar film and 0.5-mil foil, vacuum impregnated with vacuum degasified mineral base transformer oil. DC partial discharge measurements were performed with a Biddle corona test set coupled to a multichannel analyzer, and pulse height and multichannel scaling signatures of the partial discharge activity were recorded as a function of the voltages applied to the foil-edge structures. Pulse height histograms exhibited approximately Maxwellian distributions with most of the partial discharge impulses below 20 pC in magnitude. The multichannel scaling signatures, shown in the figures, were also approximately Maxwellian distributed in time, with most of the activity decaying to zero in less than 10 s. The partial discharge inception dependency on $\dot{V}$, and the apparent time constants are in reasonable agreement with the hypothesis that space charge from field-controlled injection controls the partial discharge inception voltage at the foil edges.

Impregnated 2-mil mylar/0.5-mil foil samples were observed to exhibit no partial discharges when the applied voltages were increased from 0 to ±15 kV during intervals of 1-minute risetimes. The distributions shown in Figs. 3 and 4 exhibited a marked peaking and a minor tendency to narrow in time for faster risetimes of applied voltage. It is hypothesized that when voltage is applied across the foils faster than space charge can form and reduce the field at the foil edge, partial discharges occur and create an impulsed, spatial distribution of charges in the regions near the foil edge, reducing the electric field below the partial discharge inception threshold. For conditions where $\dot{V}$ is negative (decreasing voltage), if the transient voltage is fast enough in fall time so the conduction current cannot establish a reversal, the charges trapped in the dielectric by the low mobility create an electric field by proximity with the foil edge that exceeds breakdown and partial discharges occur in the opposite direction, dissipating the excess space charge.

Because space charge formation due to charge injection is limited temporally by the magnitude of the free carrier mobility in the dielectric, a theoretically ideal impregnant would possess the electrical properties of high dielectric strength, low intrinsic/extrinsic carrier concentrations, and a high value for free carrier mobility so space charge formation times would be comparable or faster than the transient voltages applied to the foil edges.

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