FLUID INSULATION BREAKDOWN DUE TO REPETITIVE ELECTRIC FIELDS

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ABSTRACT

A facility to study the breakdown effects of rep-rate high voltage pulsing on insulating materials has been developed. The unique high voltage and data acquisition and control instrumentation are briefly described. Two insulating fluids, a transformer oil and Fluorinert FC-77(R) were subjected to increasing amplitude, 5.0 microsecond pulses at 1, 10, 100, and 1000 Hz rep-rates until breakdown occurred. These tests demonstrate a quick method for characterizing the short term voltage withstand of the materials. They also contribute to an understanding of the roles of heat and charge flow in breakdown phenomena.

INTRODUCTION

Repetitively pulsed (rep-rate, >l pps) power generation and conditioning components are currently found in a diverse range of technologies. Many of these components are used in space based, airborne, or mobile ground based systems where the prime requirements are for very high energy density and reliability.[1,2,3,4] The characteristics of the insulation and dielectric materials used within these components play an enabling role in limiting the permissible working stresses and, therefore, the energy density of the components.

There is a great deal of experimental evidence that indicates that the breakdown characteristics of insulating materials vary according to the waveform of the applied electric stresses.[5] Whereas the literature of insulating and dielectric material breakdown is extensive for ac, dc, and single pulse stresses, relatively little information exists for nanosecond and microsecond long repetitive pulses.

In liquids, many efforts have focused only on the microscopic aspects of the breakdown event: streamers crossing a gap in hydrocarbon oils. The initiation and propagation of prebreakdown and breakdown streamers in insulating fluids has been studied using optical shadowgraph and Schliren techniques.[6,7]

Prebreakdown streamers are thought to be the result of localized charge injection leading to sudden heating of a small volume of the liquid. The influence of the energy leads to vaporization of the liquid and is the most probable mechanism of bubble generation.

When the field is not strong enough for the streamer to cross the gap, the pressure and temperature in the streamer decrease. The bubble reaches a maximum size, and as the temperature decreases, the vapor condenses and the bubble disappears. When breakdown occurs, the gaseous high temperature streamer crosses the gap between the two electrodes, providing a low conductance path. A surge of high current occurs within nanoseconds.

Partial discharges created by field enhancement can also lead to localized heat regions and gas evolution in insulating fluids.[4] The generation of heat alters the chemical structure, and therefore the electrical properties of the material. The gas byproducts that evolve typically have a lower breakdown strength than that of the insulating fluid.

These studies do not incorporate the progressive effects of bubble formation, charge and heat injection that occurs with rep-rate pulsing. The decay of these quantities between pulses is seen to be most relavent to this study.

Previous work has confirmed the qualitative nature of these effects for rep-rate capacitor units and polymer films.[4,8,9,10,11] In tests of polyprolylene/silicone oil capacitors, a dramatic decrease in lifetime of capacitors at 1000 pps compared to capacitors at 250 pps was noted.[4] It was also observed that partial discharges occurred at pulse repetition rate above 250-300 pps.[4]

Mauldin[8] demonstrated that the lifetime of perfluorocarbon impregnated capacitors dropped dramatically when subjected to pulse repetition rates above 100 pps. It is also thought that the breakdown strength of the perfluorocarbons in the gas phase is very similar to the breakdown strength in the liquid phase.[4,9,12]

Early work by Treanor et.al.[10,11] compared the breakdown strength, partial discharge inception (PDIV) and extinction (PDEV) voltages, and lifetime of pulse aged and unaged polypropylene. Prestressing lowered the the PDIV and PDEV due to microscopic gas bubbles in the transformer oil at the interface between the electrode and film surfaces.

The evolution of high temperature gasses due to streamer development create impurities in the insulating fluid. The dynamic characteristics of these impurities, thermal conduction, cavitation dynamics, and charge neutralization may play a role in determining breakdown behavior. There have been some studies that have estimated the energy and pressure in bubbles formed by single step voltages.[6] To support the study of the dynamic modeling of breakdown behavior, empirical studies of the breakdown of insulation subjected to high repetition pulsing is necessary.

Testing at high repetition rates can be limited by the lack of adequate data acquisition and control instruments. Elaborate data acquisition systems are required to capture pulses at, or leading up to breakdown. The time between pulses may not be long enough to allow experimental conditions to be evaluated and necessary control functions to be performed. An automated system is needed to provide consistent measurements and control for reliable, reproducible results.

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EXPERIMENT HARDWARE

A modified SCR-548, 1 MW hard-tube pulser was used to produce the high voltage pulses. The pulser comprises a high voltage DC supply and a modulator. The modifications to the pulser allow an external trigger to control the repetition rate and output pulse width. The pulser produces 0 to -25 kV, 0.5 to 7 microsecond pulses at rep-rates varying from single shot to 1700 Hz. The leading edge risetime is nominally 100 ns.

Two liquids were chosen for this study: a general-purpose mineral oil manufactured by Shell Oil Company, Diala A(R), and a fluorinated hydrocarbon manufactured by the 3M Company, Fluorinert FC-77(R). The mineral oil is most often used to provide electrical insulation and heat transfer in electrical power devices. It is composed of predominately napthenic and paraffinic compounds. The Fluorinert liquids are derived from common organic compounds by replacement of all carbon-bound hydrogen atoms with fluorine atoms. These liquids are extremely non-polar and have essentially no solvent action. Perfluorocarbon liquids have been found to be very useful as a rep-rate capacitor impregnant,[4,8] and have been used as an insulation and coolant for high power magnetic switches.[13]

The test cell was made of glass and contained approximately 1 liter of fluid. Brass VDE electrodes were mounted horizontally in the test cell. The dimensions of the electrodes are shown in Figure 1. The VDE electrodes are hemispheres, providing a symmetrical, uniform electric field for both the cathode and anode. These electrodes are specified in the ASTM Standards for performing 60 Hz breakdown voltage tests of insulating oils.

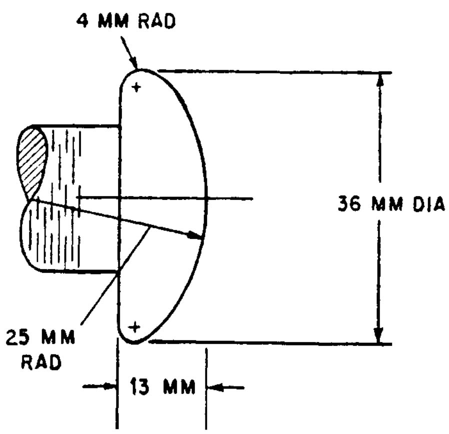


FIG. 1. Dimensions of the VDE electrodes

The electrode gap for the VDE electrodes was set by using a 75 micrometer (3-mil) sheet of polyethelyne terephthalate (PET, Mylar (R)) as a gapper. Between breakdown tests, the same PET sheet was used to flush the gap area of breakdown products. When changing the test fluid, the electrodes were removed to facilitate cleaning the test cell. This procedure permitted different gaps to exist for the different fluids, which does not allow a direct comparison of the voltage withstand of the fluids. This comparison, however, was not the intent of this study.

A novel, low cost, modular computer-based instrumentation system was developed for the rep-rate experiments.[14] The system utilizes a parallel arrangement of controlling and data acquisition units. An HP-85 personal computer serves as an overall experiment controller and user interface. A Z80 microprocessor that communicates with the HP-85 monitors and controls the experiment in progress in real time via a custom built diagnostic interface. Pulsing can be stopped immediately after breakdown. A LeCroy 9400 Digitizing Storage Oscilloscope captures a sequence of consecutive pulses leading up to and causing breakdown. For the breakdown tests performed here, the digitizing rate of the 9400 was set at 50 MHz for a sequence of 64 pulses.

EXPERIMENT PROCEDURE

The breakdown strength of the fluids was measured at 10, 100, and 1000 pps, with a 5 microsecond pulsewidth, using the following procedure: the control system triggered the pulser at the appropriate frequency while the applied voltage was nominally low. A motorized variac was then used to raise the voltage at approximately 3.4 kV/s. When the instrumentation sensed that breakdown had occurred during a pulse, the trigger pulse was removed. The tests were run in patterns which alternated the 10, 100, and 1000 pps repetition rates in order to limit the effects of aging of the fluids or conditioning of the electrodes that may have biased results. Two breakdown measurements were obtained for each repetition rate; this cycle was repeated six times.

The motorized variac was not used for the 1 pps breakdown tests due to the large (3-4 kV) increment that would occur between each pulse. Instead, the pulse amplitude was initially set at a low voltage. Five pulses at one second intervals were then manually triggered. If no breakdown occurred, the voltage was raised and pulses applied again. If breakdown occurred, the gap was cleared and the sequence applied again. As it turned out, there was a threshold voltage below which no breakdown occurred. At the next voltage level, considered the breakdown voltage, there was a breakdown before 5 pulses could be applied.

EXPERIMENT RESULTS

Typical voltage and current sequences leading up to breakdown in the 10 and 100 pps tests shown in Figures 2 and 3. The 1000 pps sequences are similar to the 100 pps sequences. Each "spike" is a time-reduced display of an acquisition window which contains the high voltage pulse. The waveform between pulses is not acquired.

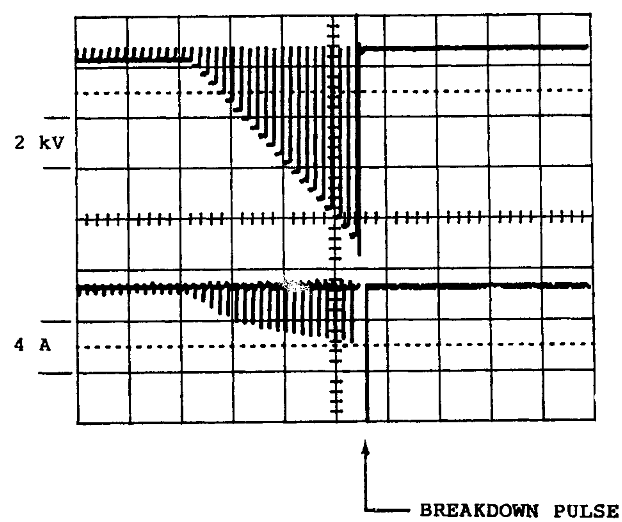


FIG. 2. Typical voltage and current sequences leading up to breakdown for 10 pps rep-rate.

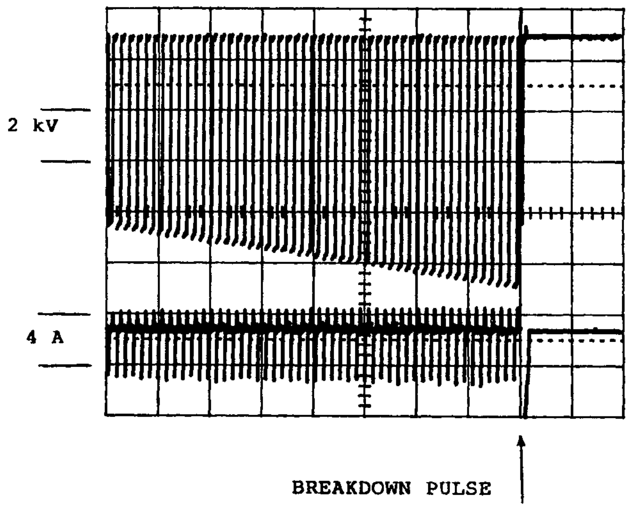
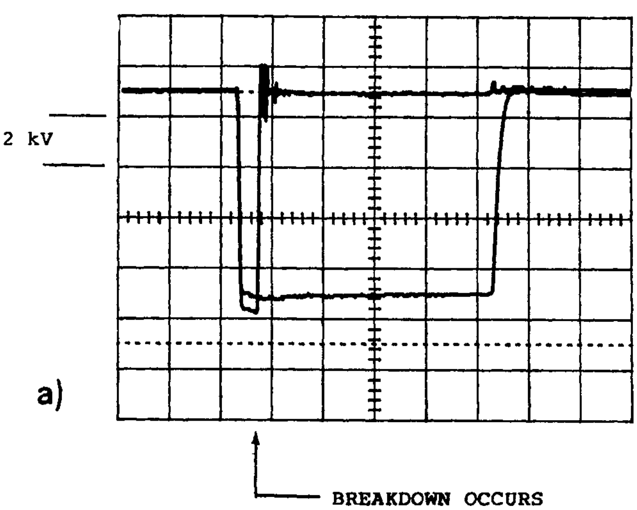


FIG. 3. Typical voltage and current sequences leading up to breakdown for 100 pps rep-rate.

While there appears to be a fairly linear increase in the peak of the applied voltage pulses, the current does not increase in the same manner. The reason for this behavior has not become completely clear. Space charge may limit the amount of injected charge at the higher voltages. The number of pulses required to show this nonlinearity at 100 and 1000 pps could not be displayed as a single sequence of pulses on the LeCroy oscilloscope.

Expanded views of typical breakdown voltage pulses and resultant current pulses are shown in Figures 4a and 4b. The pulse immediately preceeding breakdown is shown overlapped with the pulse at breakdown. The risetime (0 to 100%) was approximately 160 ns, and the falltime (100 to 0 %) approximately 360 ns. The droop of approximately 200 V occurred independently of the magnitude of the pulse. The slight abnormality in the waveform before breakdown is due to signal ringing.

The results of the tests of 5.0 microsecond pulses applied to the mineral oil and perfluorocarbon at 1, 10, 100, and 1000 pps are given in Figures 5 and 6. The average value obtained is shown by the solid symbol. The error bars represent one standard deviation.



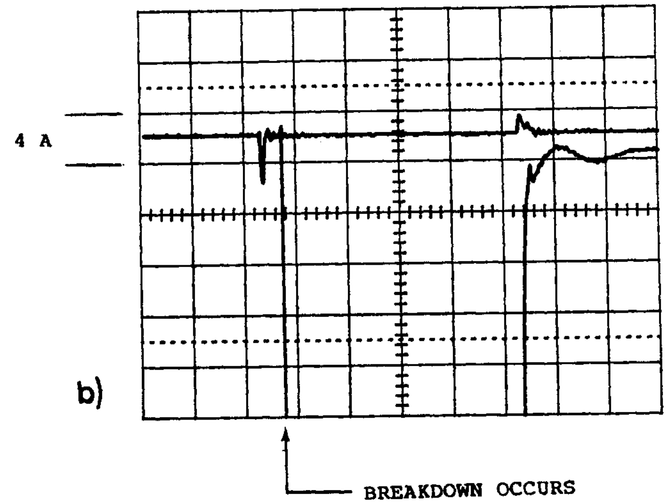


FIG. 4. Typical waveforms of pulse immediately preceeding breakdown and pulse at breakdown overlapped. (A) Voltage; (B) Current.

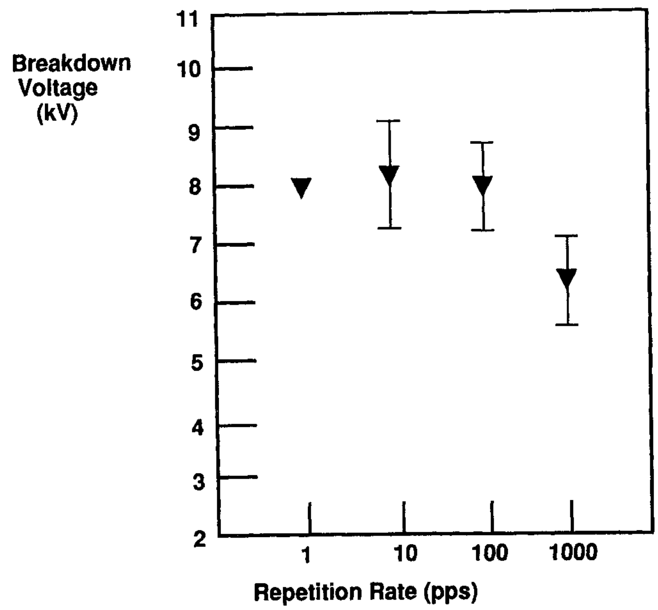


FIG. 5. Breakdown voltage of mineral oil as a function of rep-rate.

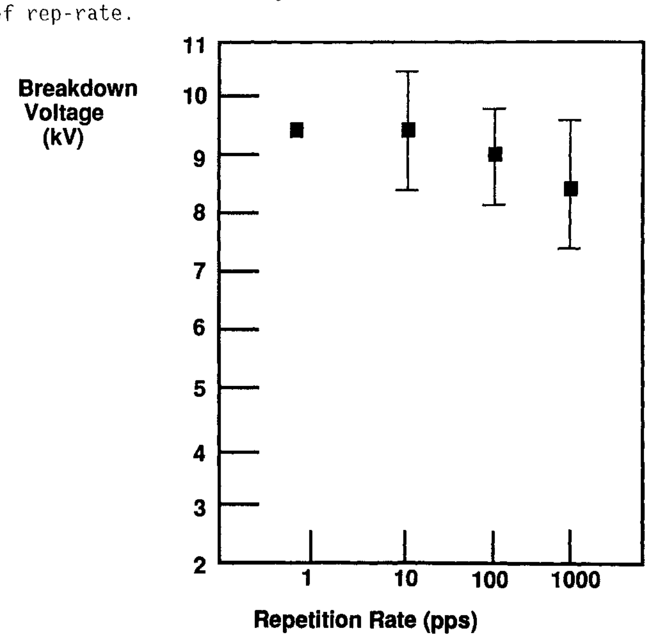


FIG. 6. Breakdown voltage of perfluorocarbon as a function of rep-rate.

There is a decrease of the average breakdown strength for both the mineral oil and the perfluorocarbon at the higher rep-rate. In the mineral oil, however, the breakdown strength is approximately 20 % lower than the values obtained at 10 and 100 pps. The reduction in the average breakdown value obtained for the perfluorocarbon at 1000 pps does not appear to be statistically significant due to the overlapping standard deviations.

Gas bubbles formed from prebreakdown streamers created by previous pulses may contribute to a reduction in breakdown strength. High temperature gasses may be the sight of partial discharge initiation, or may contribute to the propagation of breakdown streamers initiated at an electrode. In the rep-rate conditions presented here, these gasses may not have cooled, been absorbed, or dissipated in the interpulse interval.

This argument may especially apply to the mineral oil. The gasses are typically easier to break down than the liquid, thereby increasing the probability of breakdown at a low voltage. As mentioned earlier, the breakdown strength of the perfluorocarbon liquids, however, is thought to be similar in both the gas and liquid phases. This would explain the more consistant breakdown values of the perfluorocarbon, even as repetition rate is increased.

SUMMARY

Unique high voltage and instrumentation systems have been described that allow a more precise measurement of the breakdown voltage of insulation materials subjected to high repetition rate pulsing. The breakdown characteristics of two insulating fluids subjected to high rep-rate pulsing have been determined. Within the limits of the sensor and digitizing precision, it was shown that there is a charge injection threshold for the liquids. The breakdown strength of the mineral oil was lower at 1000 pps than at 1, 10, and 100 pps repetition rates. There was a more graceful degradation in the measured breakdown values for the perfluorocarbon. Continued testing with more sensitive sensors may provide insight into the thermal, gas evolution, and/or charge mobility time constants associated with breakdown in fluids.

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