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Anode-Initiated Surface Flashover*

R. A. Anderson

Sandia Laboratories

Albuquerque, New Mexico 87185

INTRODUCTION

Either of two distinctively different surface flashover mechanisms may lead to the electrical breakdown of an insulator under high voltage stress in vacuum. While the more familiar cathode-initiated mechanism propagates toward the anode and depends on secondary electron multiplication on the insulator surface (1), anode-initiated flashover propagates in the opposite direction (2) and appears to involve processes related to bulk breakdown. The study of anode-initiated flashover may therefore help to elucidate the physics of the "treeing" mode of insulation failure. In addition, anode-initiated flashover very likely limits the electric field that can be withstood by conventionally designed insulators having surfaces inclined to avoid electron multiplication.

In the work reported here, a variety of dielectric materials were subjected in vacuum (10^{-3} to 10^{-4} Pa pressure) to high voltage steps having 3 ns risetime. Damage patterns on the insulator surface characteristic of anode-initiated flashover occurred with various experimental arrangements having in common high electric fields directed into the surface of the insulator. The flashover mechanism was studied by detecting emission current from the insulator and by examining the surface damage with the aid of scanning electron microscopy. A model of the flashover mechanism based on these observations is proposed.

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GENERAL CHARACTERISTICS

Previously reported measurements of the breakdown voltage of polymethyl methacrylate (Plexiglas) conical insulators indicated that an independent surface flashover mechanism could be initiated by localized field enhancement at the anode end of the insulator and propagate toward the cathode (1). The greatest reduction in breakdown voltage due to anode-initiated flashover was found with insulators having angles between about +40° and +70°, that is, insulators oriented as shown in Figure 1(a). The prebreakdown time delay under these circumstances was found to vary inversely as the cube or higher power of the applied voltage, unlike the inverse square proportionality typical of cathode-initiated flashover. According to these measurements, the two types of flashover are of equal importance in the breakdown of conventional +45° insulators. Why the range of angles between +40° and +70° facilitated the anode-initiated mechanism is unclear, but such angles may represent a compromise between field enhancement at the anode end of the insulator, which increases as the angle increases (2), and the average value of the field component parallel to the insulator surface, which decreases as the angle increases.

The extreme speed of the anode-initiated flashover mechanism demonstrates that it is electronic in nature, rather than a positive ion analog of the secondary electron emission avalanche responsible for cathode-initiated flashover. For example, electrical breakdown of a +60° Plexiglas insulator bridging a 6 mm interelectrode gap can occur within 2 ns after voltage application. During this time a freely accelerated proton, the fastest positive ion, would travel only a fraction of the gap distance.

CONDITIONS OF OCCURRENCE

In each of the three different experimental arrangements shown in Figure 1, dendritic patterns of damage characteristic of anode-initiated flashover were produced on the insulator surface by the application of a pulse-voltage stress. Figure 1(a) is the case of a 60° insulator between parallel electrodes, where flashover resulted in an abrupt collapse of the insulator impedance on a nanosecond time scale. In (b) and (c), however, interelectrode breakdown could not occur. Arrangement (b) permitted the detection of emission currents from electrically stressed insulators, discussed in the next section. Damage patterns were confined to the anode-facing surface of the insulator within the high-field central region. Figure 1(c) depicts an attempt to grow "trees" into the bulk of the insulator. Surprisingly, visible streamers were found only on the surface of the insulator facing the holes in the anode electrode, and they branched toward the center of each hole from the high-field region at the edge.

The patterns of damage produced under these three different circumstances were nearly identical, both in their appearance to the unaided eye and in the microstructure observable with a scanning electron microscope. Furthermore, as indicated in Figure 1, the electric field in each case was directed steeply into the surface of the insulator. It is therefore reasonable to assume that the flashover phenomena occurring in all three cases were the same. Accordingly, this type of surface flashover may account for the electron emission from the dielectric observed when electron beam cathodes contain dielectric inlays (1).

EMISSION CURRENT

Anode-initiated flashover is accompanied by emission of negative charge from the insulator surface into the vacuum. Bursts of current of the order of 0.1 A/m^2 and a few ns in duration were detected by a Faraday cup located behind a perforated anode electrode which was separated from the insulator surface by a vacuum gap. Figure 1(b) is a diagram of the experimental arrangement. Such emission was observed from all the dielectric materials tested when the electric field in the vacuum gap exceeded 40 or 50 MV/m. These materials included polymethyl methacrylate (Plexiglas), polyethylene, polyethylene terephthalate (Mylar), polyimide (Kapton), Corning 0211 cover slide glass, and insulator surfaces covered with either silicone grease or silicone diffusion pump fluid. The quantity of charge emitted during a single high-voltage pulse was found to correspond to the collapse of the electric field in the vacuum gap. G. P. Frazier of Physics International Co. has made similar observations of the emission from Plexiglas insulators (5).

The surfaces of our polymeric dielectrics were invariably found to bear the previously mentioned damage patterns after emission had been detected. Although no markings were visible on the glass surface, due perhaps to the thermal stability of glass, the characteristic dendritic patterns could be seen in the condensation of breath on the glass surface. One may conclude that anode-initiated flashover is not restricted to a few special dielectrics.

Field extraction of electrons and negative ions from the flashover plasma is thought to be responsible for the emission current. The time delay before emission varied widely, from a few ns to much longer times, indicating a wide variation in the flashover inception time in this experimental arrangement. Often several pulses occurred within a 10 to 20 ns period, possibly the result of a time-of-flight mass analysis of various ions arriving at the Faraday cup. A conditioning effect was also observed, in which higher voltages were required to cause emission on subsequent pulses although the insulator had been discharged between pulses by the admission of air into the vacuum chamber.

SURFACE DAMAGE

Information about the anode-initiated flashover mechanism is recorded in the damage on the insulator surface. Figure 2 is a rough sketch of the intricate pattern, typically resembling a tree, which results from an interelectrode flashover in the geometry of Figure 1(a). The prolific branching indicates that the insulator became conductive, distorting the local electric field, closely behind the leading edge of the flashover mechanism, which allowed the flashover to grow laterally as well as toward the cathode. This conclusion is supported by the arrested growth of the pattern apparently the instant a branch reached the cathode, and by greater surface damage near the cathode end of the insulator such as would be expected if most of the potential drop occurred between the developing flashover and the cathode electrode. Furthermore, a conspicuous lack of enhanced damage along the main branches and trunk of the pattern is consistent with the rapid formation of the flashover plasma, so that the damage was confined to the growing tips of the branches.

The microstructure of the damage reveals how rapidly the plasma may have formed. The inset in Figure 2 shows a branch tip magnified several hundred times. Numerous filamentary grooves, a micron or less in width and depth, curve away from the branch axis and extend for tens of microns, some developing side branches of their own. The ends of these grooves are frequently aligned nearly perpendicularly to the parent branch axis, and some of the grooves appear to burrow into the bulk of the insulator. These observations suggest that the flashover plasma formed so closely behind the branch tip that the local electric field changed direction during the time the side branches were growing. As the region of conductivity advanced past a point along a branch, the electric field on either side of the branch would have decreased considerably as it rotated to a nearly perpendicular orientation relative to the branch axis.

Although the surface damage on the four polymers tested was similar, there were interesting differences. With Kapton, for example, chains of evenly spaced pits about a micron in diameter, rather than grooves, defined the course of small branches. Presumably the lack of grooves was due to the high thermal stability of Kapton. There was a pronounced tendency for the pits, or grooves in the case of the other polymers, to display a 5 to 10 micron periodicity, and for branches to follow microscopic scratches.

DISCUSSION

A model of the anode-initiated flashover mechanism which accounts for the experimental observations may be proposed. Flashover initiation is assumed to require the generation of a small area of plasma adjacent to the insulator surface. The plasma is maintained near the anode potential, either from being connected to the anode electrode or through electron emission. As a result, the edge of the plasma contributes a strong electric field component parallel to the insulator surface. Filamentary branches develop because the electric field at their tips presumably exceeds the dielectric strength of the material. Localized breakdown at the branch tips, the cause of the surface damage, generates the new plasma necessary to carry the field enhancement forward. The growth of filaments into the bulk of the insulator is assumed to be arrested when the surface plasma advances past their point of entry and the electric field is reduced. Photoemission, photodesorption, or photoconductivity may play a role in this flashover mechanism since ultraviolet light is undoubtedly produced.

The preceding discussion does not consider how the plasma is generated at the point of initiation. In the experimental arrangements of Figure 1(a) and (c), localized electric fields at points of contact between the insulator and the anode electrode may exceed the dielectric strength of the insulator. The source of the initial plasma in the geometry of Figure 1(b) is unclear, although the conditioning effect mentioned earlier points to the involvement of either gaseous or particulate contaminants on the insulator surface.

Finally, it is of interest to note that the apparent relationship of anode-initiated flashover with bulk "treeing", evidenced by the penetration of damage into the insulator, may have physical significance. Plexiglas insulators suffering bulk breakdown under nanosecond-pulsed conditions were found to contain "trees" that originated almost exclusively at the anode surface (6).

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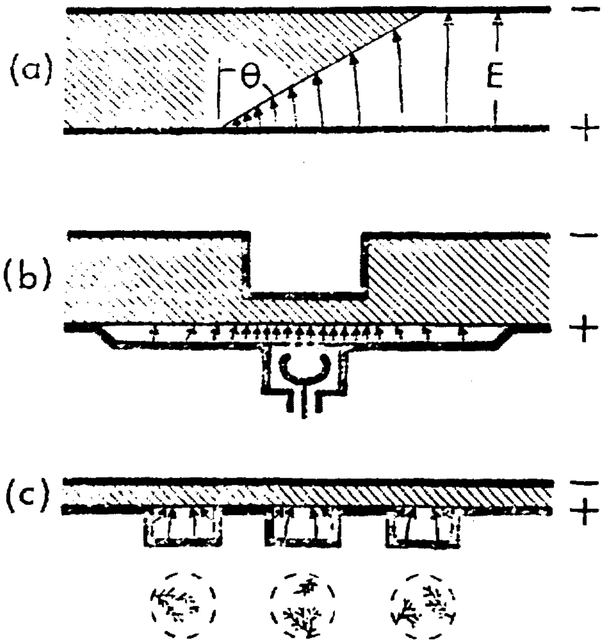
FIGURE CAPTIONS

Fig. 1 Experimental arrangements favoring anode-initiated flashover (shown in cross section). Arrows indicate the electric field in the vacuum. (a) Positive-angle insulator (θ = +45°), (b) arrangement for observing emission, (c) holes in the anode electrode.

Fig. 2 Sketch of the surface damage on polymeric dielectrics, showing an [illegible] branch tip.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