

IMPROVED VACUUM SURFACE FLASHOVER PERFORMANCE OF POLYMER INSULATORS BY THE USE OF UNIQUE TRIPLE JUNCTION DESIGNS*

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Abstract

Previous research and theories about surface flashover in vacuum indicate that the triple junction region plays a critical role in the insulator flashover process. To attempt to improve upon the performance of the standard 45-degree frustum insulator, three different insulator geometries with modified triple junction regions were investigated. Two samples of each geometry, each 2 cm thick, were tested to obtain the flashover voltage levels in a 10^{-5} Torr vacuum using a 1.2-microsecond risetime voltage pulse. Each sample was tested five times with 20 shots per test for a total of 200 shots per geometry.

Test results and comparisons of the flashover voltage levels for the four geometries are presented. One geometry showed an improvement in flashover voltage of about 40% over the standard 45-degree frustum. It also showed significantly less susceptibility to low-voltage flashover due to surface damage, suggesting a correlation between surface damage and the development of conductive paths along the surface.

Introduction

The triple junction region plays an important part in the surface flashover process [1]. Most theories and experimental evidence indicate that the surface flashover voltage level of an insulator is dependent on the electric field strength at the cathode triple junction region. Our initial goal was to see if certain geometries would lead to a lower cathode triple junction field, resulting in a higher holdoff voltage. Four geometries, shown in Fig. 1, were chosen to investigate this possibility.

The first geometry consisted of the commonly investigated and applied 45-degree frustum. The second geometry consisted of a special design that would lower the field at the triple junction region. The third geometry is a modification of the second geometry, and the fourth geometry added an embedded conductor to radically lower the field at the triple junction region.

Figure 2 shows a typical secondary electron emission coefficient curve as a function of primary electron energy for a typical insulator. Electrons with energy greater than A2 impacting the insulator surface will leave the insulator negatively charged at the region of impact. This charge will probably consist of both surface charging and

near-surface bulk charging. Referring to Fig. 3, if charging of the insulator surface across from the triple junction region occurs, then a lowering of the electric field at the triple junction region would occur.

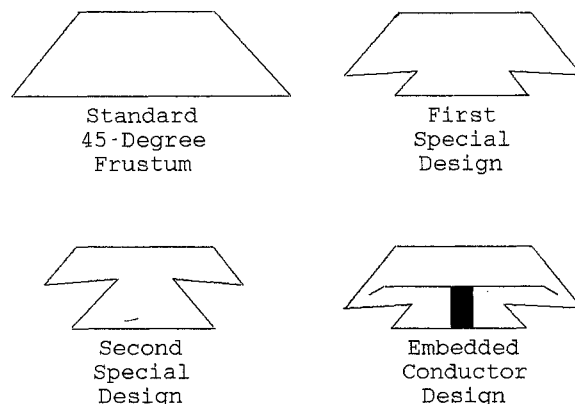


Figure 1. Side view of standard 45-degree frustum and three special insulator designs.

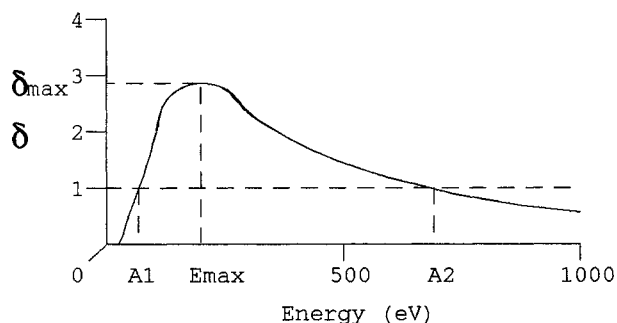


Figure 2. A typical secondary electron emission coefficient curve for an insulator.

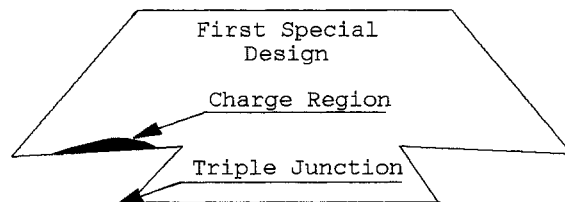


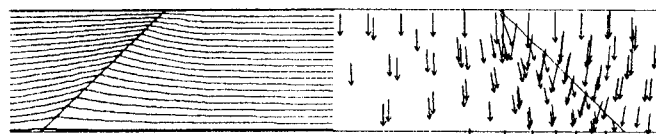
Figure 3. First special design sample showing the triple junction location and the region of negative charge buildup.

Figure 4 shows electric field and equal potential line plots for the four geometries. These plots were created using a finite element analysis code on a Sun computer. Analysis of these plots indicate that the electrons

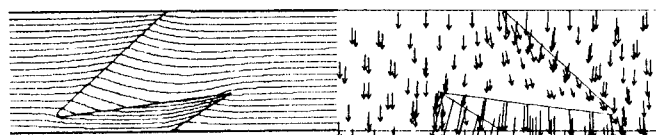
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14. ABSTRACT Previous research and theories about surface flashover in vacuum indicate that the triple junction region plays a critical role in the insulator flashover process. To attempt to improve upon the performance of the standard 45- degree frustum insula tor, three different insulator geometries with modified triple junction regions were investigated. Two samples of each geometry, each 2 em thick, were tested to obtain the flashover voltage levels in a low 10- 5 Torr vacuum using a 1. 2- microsecond risetime voltage pulse. Each sample was tested five times with 20 shots per test for a total of 200 shots per geometry.					
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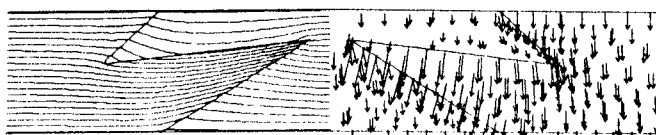
impacting the region opposite of the triple junction should have sufficient energy, greater than A2, to cause a negative charge buildup. Whether or not this charge buildup will be sufficient to noticeably influence the surface flashover voltage depends on a few factors. First, there is a charge leakage rate that is dependent on the amount of charge buildup, material, and local electric fields. Second, there is a deposition rate that depends on the holdoff voltage of the insulator and the shape, voltage, and repetition rate of the pulses applied. The deposition rate is also dependent on the field at the triple junction, material, and the energy of the electrons impacting the surface.



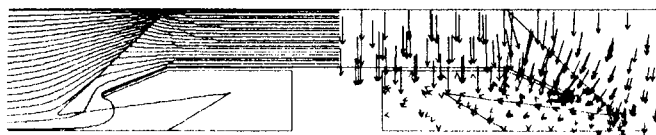
Standard 45-Degree Frustum



First Special Design



Second Special Design



Embedded Conductor Design

Figure 4. Electric field and equal potential line plots for the four geometries.

Three possible outcomes of surface charging can occur. First, the charge buildup is limited by the leakage versus deposition rate. Second, the electric field at the triple junction falls to a low enough point to quench the field emission from the triple junction. Hence, the charge buildup is limited to the amount producing this critical electric field. Third, the charge buildup is limited by the electron energy impacting the insulator surface. Referring to Fig. 2, if the electric field in the region between the triple junction and the charge region falls to a low enough point, then the energy of the electrons impacting the insulator will stabilize at A2. This stabilization of the electron energy corresponds to a stabilization of the charge buildup and resulting electric field.

Referring to Fig. 4, all three special designs have the added advantage of possibly trapping triple-junction-emitted electrons in

the recessed region of the insulator. How well this process works to increase the flashover voltage level is probably dependent on pulse duration. All four geometries have the added holdoff voltage advantage of the 45-degree sloping outer-profile in comparison to a cylinder [2]. Depending on the amount of charge buildup, the first two special geometries could also provide an extra radial component of the electric field that would drive electrons away from this outer-profile surface. The embedded conductor design is, in a sense, an extreme case of the first special design. It has a substantial radial component to drive electrons away from the 45-degree sloping surface.

Experimental Setup and Procedure

The ability of each design to effectively prevent the occurrence of surface flashover was tested through experimentation performed at the Bushing Test Facility at Los Alamos National Laboratory [3]. The 11-stage Marx bank has one 80-nF, 100-kV capacitor per stage and can be charged to a maximum energy of 4.4 kJ by a 100-kV, 18-mA DC power supply. The Marx bank is capable of providing pulses with voltages up to 1 MV.

Samples were tested between stainless steel electrodes formed to a Bruce profile. These Bruce profile electrodes provide a fairly uniform field in a gap ranging from 0 to 16 cm.

All four geometries were originally manufactured out of Lexan, a General Electric polycarbonate. The second manufacturing of the embedded conductor design used an acrylic resin.

Two samples of each geometry were manufactured, with the exception of the second special design in which four were created. Two samples of each embedded conductor type were created. All designs were machined to be 2 cm high and, at most, 10 cm in diameter.

The first manufacturing process for the embedded conductor sample involved cutting two pieces of Lexan and painting a thin conducting film (50% silver by weight) on the top surface of one of the pieces. A small copper wire surrounded the edge of the film to prevent high local fields. Methylene chloride was applied to the bottom of one of the pieces and the remaining Lexan surface on the top of the other piece to dissolve the Lexan. The pieces were then firmly pressed together and allowed to dry. The second manufacturing process for the embedded conductor sample involved casting a small copper electrode in an acrylic resin. After the resin had hardened, the acrylic was machined into the desired geometry.

The electrodes were polished with very fine Scotch-brite pads before each test to remove markings produced by previous flashovers. The electrodes were then cleaned with freon and wiped dry with lint-free paper towels to remove any film left by the freon.

Each sample was prepared before testing. Whiskers and carbon tracks from previous flashovers were removed by sanding the sides of the insulator samples with #1000 grit sandpaper before each test. The bases of the samples were sanded with #2000 grit sandpaper to insure that the samples made a tight fit with the electrodes. The samples were then cleansed in distilled water in an ultrasonic cleaner for several minutes. Next, using rubber gloves, the samples were scrubbed with a

brush, recleansed, blown dry, and placed between the Bruce profile electrodes. Finally, dry air was used to blow stray dust particles away from the sample and electrodes.

The vacuum chamber was sealed and allowed to pump down overnight (approximately 16 hours) to a pressure of about 1×10^{-5} torr. The vacuum system consists of two 12-inch, cold-trapped diffusion pumps and a roughing pump system.

For a given test, the sample was pulsed at 10-minute intervals for, at most, 20 pulses. The 10 minute delay was included to allow for surface charge redistribution on the sample. A 1.2- μ s risetime (10%-90%) pulse was used, and the Marx bank was charged to a voltage which insured that the sample always broke down on the rise of the pulse.

The voltage waveform for each shot was recorded by a digital oscilloscope. The flashover voltages, corresponding to the maximum negative voltages recorded (negative polarity), were calculated by a max-min program incorporated into the oscilloscope. This data was recorded for statistical analysis and graphed on a Macintosh II computer.

Results

Due to the nature of the flashover phenomena, the statistical spread of most flashover data is large. For this reason, a statistical approach of obtaining a large amount of data and averaging that data in order to see trends was chosen. All error bars represent the standard deviation of the mean, which is defined as the standard deviation divided by the square-root of the number of events. The standard deviation of the mean signifies an error in the estimate of the average [4].

The original embedded conductor design broke down at low voltages because of a poor bond between the two adjoining pieces of Lexan. The improved embedded conductor design, made by casting the conductor in acrylic, failed due to bulk breakdown near the edge of the embedded conductor. Both samples of both designs failed on the first shot. Therefore, the voltage results are of little value in comparison to the results of the other geometries and will not be presented.

Table 1
Average Flashover Voltages of Samples

(kV)	Standard 45-degree Frustum	First Special Design	Second Special Design
Average First	324.84 ±8.22	286.03 ±17.73	326.99 ±15.50
Average Highest	342.08 ±3.89	353.58 ±3.35	443.42 ±8.02
Average Lowest	176.43 ±12.01	190.45 ±13.22	288.90 ±13.24
Grand Average	274.11 ±4.40	292.50 ±3.73	378.74 ±3.35

Table 1 summarizes the results of the 45-degree frustum, the first special design, and the second special design tests. The average first-shot, average highest, and average lowest

values have been calculated from ten different tests for each design. Each test consisted of 20 pulses, and thus, the grand average is calculated from 200 flashover voltages.

The data in Table 1 is graphically shown below in Fig. 5. The shot-by-shot average of the ten samples for each of the three geometries is presented in Fig. 6.

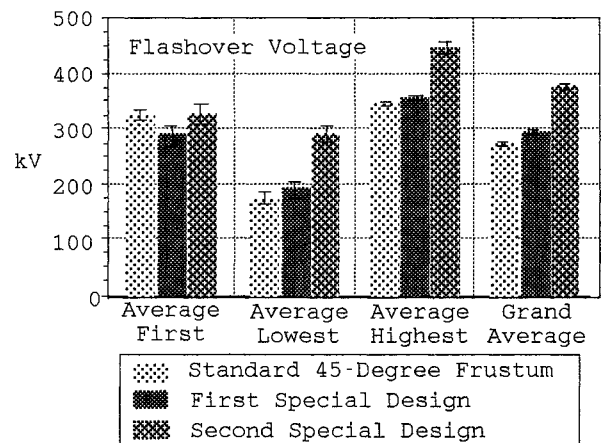


Figure 5. Average flashover voltages of insulator samples.

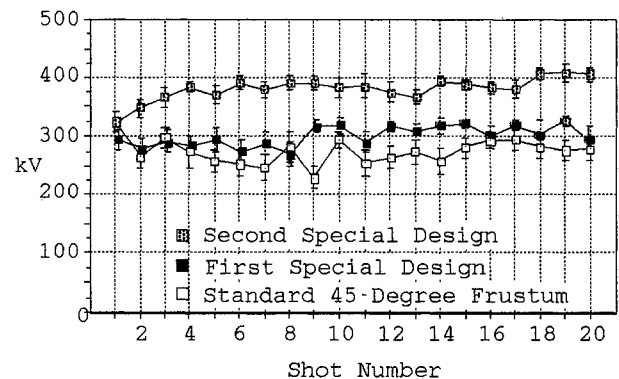


Figure 6. The shot-by-shot flashover voltage average of ten samples for each geometry. Every point and corresponding error bar are computed from ten flashover events.

Discussion and Conclusions

The grand average breakdown voltage of the first special design is 7% higher than the standard 45-degree frustum, and both designs seem susceptible to surface flashover at low voltages resulting from various forms of damaging. However, in the case of the first special design, surface flashover at low voltages seemed to occur because of a unique form of damaging.

As determined by photographs of flashover events and analysis of electrodes and samples, the first few flashovers originated at the triple junction, tracked up into the recess of the insulator, tracked back along the top, and rounded the outer tip to the anode. As the arc rounded the outer tip, the region of the cathode directly beneath the outer tip melted. The sharp microprotrusions that were formed produced high local electric fields and, hence, an arc from the cathode directly to the outer tip of the insulator. Burning of the cathode

region is evidenced by intense etched marks and brown discoloration on the cathode surface which was observed after each test run. Arcing from the cathode directly to the outer tip of the insulator is evidenced by severe brown discoloration and some electrode material on the surface of the outer tip of the insulator.

The outer tip of the second special design is located further from the cathode. As a result, this design seemed much less susceptible to low voltage flashover resulting from various forms of damaging. The average lowest breakdown voltage is 64% higher than the average lowest breakdown voltage of the 45-degree frustum while the grand average is 38% higher. Also, there is no evidence of arcing from the cathode to the outer tip. In addition, flashovers for this second special design, as well as the first special design, did not travel continuously along the surface of the insulator. Rather, the flashovers arced from the lower angled recessed portion to the upper angled recessed portion of the insulator. The arcs consistently left the lower portion at a generally local region, but the landing point of the arc seemed quite random. Figure 7 displays the arcing nature of the first and second designs.

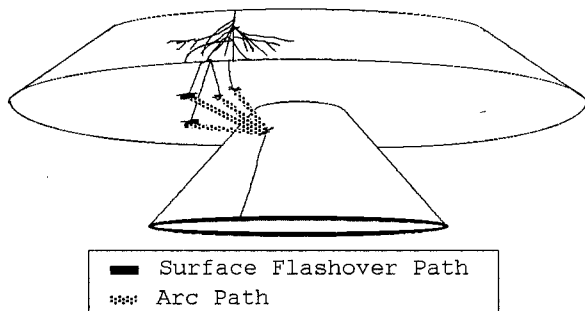


Figure 7. An illustration demonstrating the arcing nature of the first and second designs.

The competing processes of damaging and conditioning can produce fluctuating holdoff voltages for an insulator [5]. Damaging of an insulator is evidenced by dendritic carbon paths on the insulator's surface. The Joule heating from pre-breakdown currents which flow along the carbon paths possibly increases the rate of gas desorption and ultimately increases the probability of surface flashover. However, damage can be "healed" by a form of conditioning in which subsequent flashovers heat the insulator's surface, which causes the carbon tracks to become discontinued [5].

Depending on the energy of the arcs and the amount of surface damage that occurs, along with other parameters, various forms of conditioning may actually increase the flashover voltage level of later shots. Referring to Fig. 6, the second special sample indicates a conditioning-dominated process. The standard 45-degree frustum does not indicate this. As a result of the arcing in the recessed region of the second special design, a continuous carbon path from the cathode to the anode cannot form, and thus, lower pre-breakdown currents flow, resulting in higher flashover voltages. A similar process is responsible for the higher flashover voltage level obtained with a roughened insulator surface in comparison to a smooth surface [5]. A roughened surface is less likely than a

smooth surface to develop, from flashover events, continuous carbon paths from the cathode to the anode.

Another interesting characteristic of this design was the occurrence of bulk breakdown. Four samples were needed for this design to obtain ten complete runs of surface flashover voltages. Two of the samples failed due to bulk breakdown during their third test run while one sample exhibited bulk breakdown during the second test run. In each case, bulk breakdown began at an area located in the recessed upper surface of the sample and continued directly through the material to the anode.

Bulk breakdown for 1 cm of Lexan should occur well above the test voltage applied. It is possible that the insulator accumulated a negative surface and bulk charge which effectively reduced the thickness of the insulator in that region. This is evidenced by the fourth sample which survived five complete runs without bulk breakdown but showed internal brown discoloration which is characteristic of charge stress.

Although the original research goal of detecting an increase in the surface flashover voltage due to a charge buildup in the upper portion of the recessed surface was not directly obtained, it still may be a viable process, and interesting results governing the behavior of the second special design was obtained.

The samples of the embedded conductor design which were fabricated did not perform well, however, the electric field plots indicate that the embedded conductor produces an extremely low field at the triple junction. Thus, if a more reliable design is developed, much higher holdoff voltages should be obtained.

Acknowledgements

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