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Analysis of Flashover Characteristics under Nanosecond Pulsed Coaxial Electric Field

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ABSTRACT

Under nanosecond pulsed coaxial electric field, surface flashover voltage over the interfaces between nylon 1010 and transformer oil increases almost linearly with gap length, and the steeper rising edge of applied pulse, the higher flashover voltage. Surface flashover properties are closely related to the electric field at the triple junctions of solid-liquid-electrode and the field gradient along the interfaces. Although the increased difference between inner and outer electrode radii will enhance electric field strength at the triple junctions and nonuniformity degree of potential distribution along interfaces, it reduces simultaneously terribly the surface field strength of coaxial inner electrode, so that flashover voltage doesn't descend, but ascends almost linearly with gap length. The average flashover strength in coaxial electric field can be estimated by that in uniform electric field for large enough difference between inner and outer electrode radii, which is useful to practical engineering design for coaxial pulsed power apparatuses.

Keywords: *Pulsed Power Technology, Coaxial Electrodes, Gap Length, Surface Flashover, Triple Junctions, Surface Potential*

1. Introduction

Although coaxial pulsed power apparatuses are widespread, researches on discharge characteristic over transformer oil/solid interfaces under nanosecond pulsed coaxial field, as opposed to discharge characteristic over gas/solid or vacuum/solid interfaces under uniform field, are less, which can't meet the rapid development of pulsed power technology [1−7]. Surface flashover, whether applied dc, ac or impulse voltages, are closely relevant to potential distribution gradient along interfaces between different dielectrics. Trinh [8] and Menju [9], respectively, pointed out the relationship between flashover field strength and different parameters of coaxial experimental electrodes might be speculated on through corresponding states of potential distribution along the interfaces and field strength at triple junctions. Liu [10] plotted the varying curve of breakdown voltage vs. nonuniformity degree of electric field in electrode gap in transformer oil, discovered that breakdown voltage in uniform field was about three times higher than that in nonuniform field under applied impulse voltage of pulse-width of 40 µs, and achieved that change of uniformity degree of electric field in gap worked on breakdown voltage more prominent under impulse voltage than under ac voltage. This contribution analyzed flashover characteristic over transformer oil/nylon 1010 interfaces under coaxial nanosecond pulsed field in the case of changing radius difference between inner and outer electrodes from the viewpoint of potential distribution over the interfaces and field strength at triple junctions, and compared flashover properties in coaxial field with ones in uniform field, thus draw conclusions useful to studying flashover over interfaces between different dielectrics and to the developments of pulsed power technology.

2. Experimental Setup and Methods

The entire structures of electric connection of experimental setup are shown in Figure 1. The high voltage nanosecond pulsed power supply is SPG200 based on Semiconductor Opening Switch (SOS) in Northwest Institute of Nuclear Technology, whose amplitude of output voltage which can reach maximum 350 kV is modulated by adjusting the resistor of cycling salt water. A resistor of 200 Ω is in series with electrode gap in order to avoid excessive current of gap breakdown impairing SPG200 [11,12]. An impulse of pulse-width of about 30 ns, rising edge of about 10 ns, is produced by SPG200. Accordingly, the waveforms of breakdown voltage and current

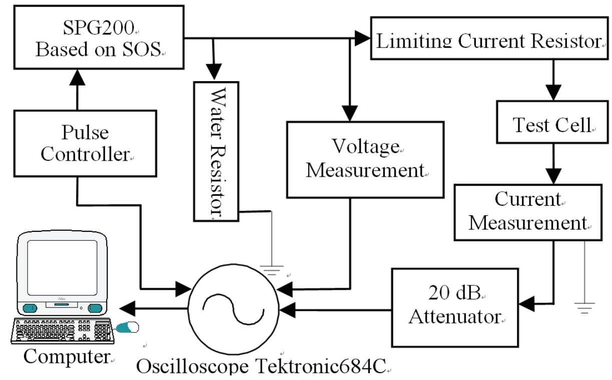

Figure 1. Schematic diagram of experimental setup

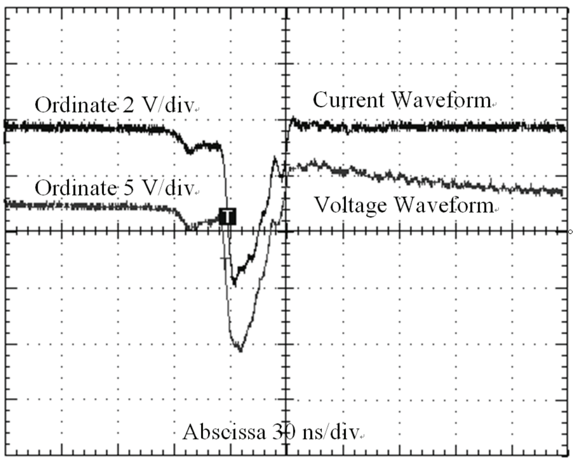

Figure 2. Voltage and current waveforms with no gap

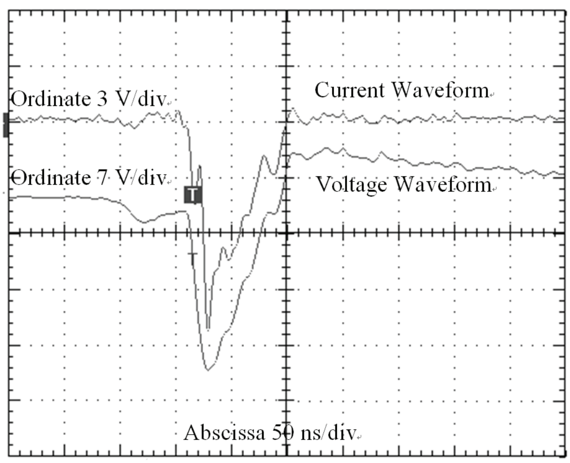

Figure 3. Breakdown voltage and current waveforms

for the direct short gap and for flashover, respectively, are shown in Figure 2 and Figure 3. Breakdown voltage and current signals, whose data acquisition and processing were executed by an oscilloscope of Tektronic684C combined with a computer, were attained by a capacitor divider and a resistor divider respectively [13].

The coaxial brass testing electrodes shown in Figure 4 should be characteristic of carefully coaxial structures, should be ensured to contact tightly with experimental solid samples and to replace solid samples conveniently, should be long enough in axis to avoid the influence of edge-effect of coaxial field on flashover over solid/liquid interfaces [14]. Solid samples of nylon 1010 with axial length of 6 mm were given shape to round ring. The liquid dielectric was transformer oil, marked 45 numbers, with industrial desiccating, filtrating and degassing.

Flashover voltage was described as the voltage applied between inner and outer electrodes while gap breakdown happened at the front edge of impulse voltage whose amplitude was about 135 kV, waveform of 10/20 ns, and two kinds of steepness of rising edge of 7.8 kV/ns and 8.6 kV/ns. The change of gap length of 1, 2, 3, 4 mm was achieved through the according change of diameter of outer electrode of 8, 10, 12, 14 mm, at the same time retaining the diameter of inner electrode of 6 mm. The total number of solid samples in same size and shape was five, and every solid sample was tested four times between them an interval of 10 min was introduced [15,16]. It is very necessary to replace solid sample, transformer oil after flashover for four times and experimental electrodes as etched spots have shown on the surface of electrodes.

3. Results and Discussion

3.1 Flashover Voltage and Gap Length

For two different kinds of steepness of rising edge of applied voltage impulse, experimental data for flashover voltage U_f of nylon 1010 vs. gap length D were shown in Figure 5 in which every datum point was the average of 15 times tests and was associated with a standard deviation. It is observed from Figure 5 that U_f of nylon 1010 increases almost linearly with D. As a result of surface flashover of rising edge of applied impulse, U_f is hardly

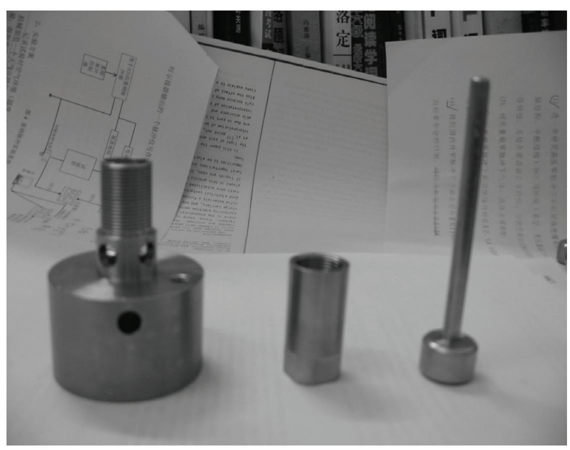

Figure 4. Brass electrodes

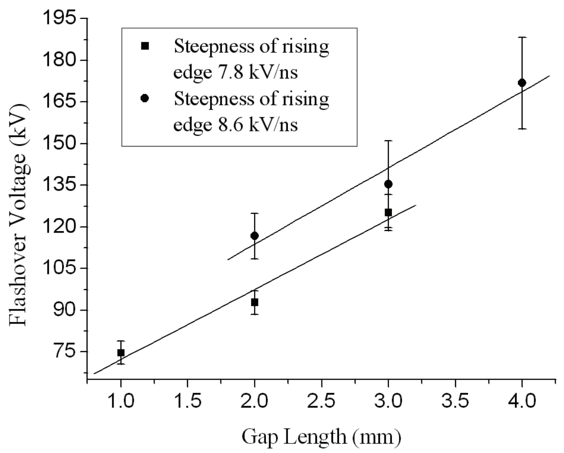

Figure 5. Flashover voltage according to variable gap length

affected by the amplitude of applied impulse, whereas remarkably by the rising edge of applied impulse. For example, U_f of nylon 1010 is enhanced about 15 kV with the increase of 1 kV/ns in the steepness of rising edge of applied impulse at the gap length of 3 mm.

3.2 Simulation Analyses of Experimental Results

3.2.1 Field Strength at Triple Junctions

The factor λ of field strength improvement at triple junctions is defined by

$$\lambda = E_j / E_m, \quad (1)$$

where E_j is the field strength at triple junctions, E_m is the average field strength along solid/transformer oil interfaces and denoted by

$$E_m = U_0 / D, \quad (2)$$

where U_0 is the amplitude of applied static voltage, D is gap length. A λ_i for field strength improvement factor at triple junctions at inner electrode surface as well as a λ_o for that at outer electrode surface varying with gap length D is shown in Figure 6 in whose legend are λ_i and λ_o. From Figure 6, on the one hand the λ_i, far greater than 1, increasing rapidly with D indicates the field strength E_i at triple junctions at inner electrode surface is enhanced to a certain extend and is, along with the increase of D, more and more higher than the average field strength E_m; on the other hand the λ_o, at all time less than 1, decreasing nearly linearly with D indicates the field strength E_o at triple junctions at outer electrode surface is always lower than E_m. The above opinions imply, under coaxial non-uniform field, because of E_i far greater than E_o surface flashover over solid/transformer oil interfaces should begin from the triple junctions at the inner electrode surface whose physical, chemical natures would character flashover properties. As a result for a single reason, the increase of D would enhance E_i, consequently reduce U_f which contradicts the experimental phenomena.

3.2.2 Potential Distribution along the Interfaces between Nylon 1010/Transform Oil

The nonuniformity degree γ of potential distribution over the interfaces between nylon 1010/transformer oil is defined by

$$\gamma = P_{max} / P_{min}, \quad (3)$$

where P_{max}, P_{min} respectively stand for the maximum, minimum potential gradient in unit length along the interfaces. That the γ increases almost linearly with D should be the other reason for declining U_f, which also contradicts the experimental phenomena.

3.2.3 Field Strength at the Surface of Inner Electrode

When flashover occurs, that the field strength E_{in} at the inner electrode surface varies with gap length D is shown in Figure 8, where E_{in} reduces nonlinearly rapidly with D. This is the only positive reason for U_f to increase with D. From Figure 6 and 7, U_f should decrease with D, but inversely from Figure 8. So under the combined effects of the above three reasons U_f behaves to increase almost linearly with D. It is sure that the positive effect of E_{in} on the surface flashover shown in Figure 8 is intense enough to counteract the negative effects of λ and γ shown in Figure 6 and 7 respectively, so that U_f increased almost linearly with D.

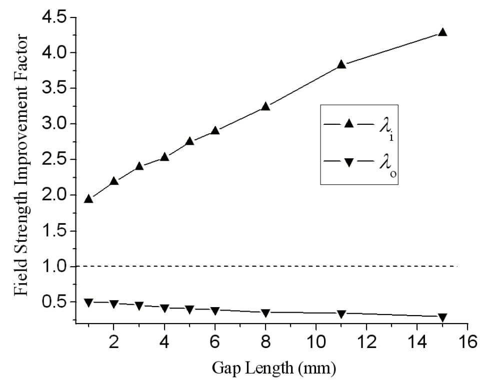

Figure 6. Field strength at triple junctions vs. gap length

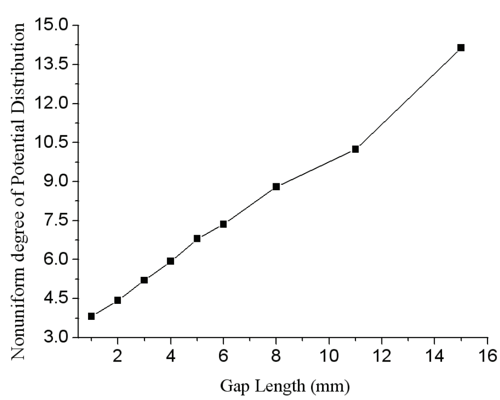

Figure 7. Potential distribution along the interfaces vs. gap length

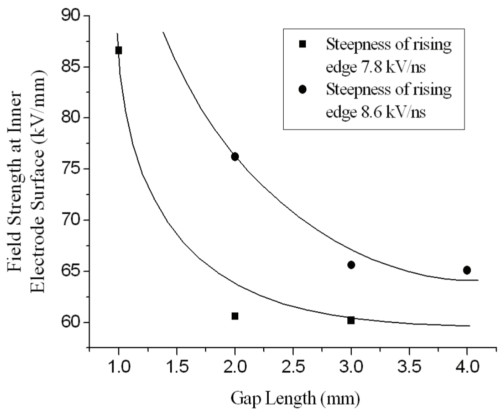

Figure 8. Field strength at the inner electrode surface vs. gap length

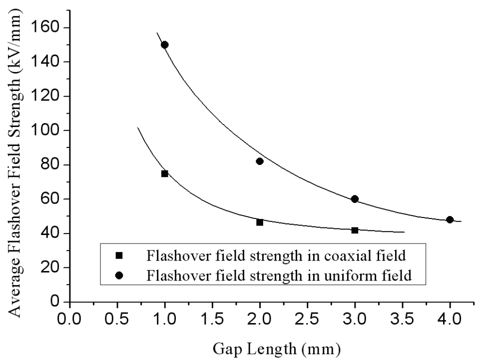

Figure 9. Flashover comparison between coaxial and uniform field

The above statement indicates , in a general way, the higher field strength at solid-liquid-electrode triple junctions as well as the more nonuniform potential distribution over the interfaces between different dielectrics should lessen the resultant flashover voltage, however, under the actual circumstances, one should think over all sorts of factors working on flashover, otherwise would receive false results.

3.3 Comparing the Results under Coaxial Electric Field with Those under Uniform Field

The average flashover field strength E_{av} in the coaxial field was compared with that in the uniform field in Figure 9. E_{av} equals to flashover voltage U_f divided by gap length D in the coaxial and uniform field respectively, i.e.

$$E_{av} = U_f / D. \quad (4)$$

The E_{av} in the coaxial field is lower than that in the uniform field for the same solid samples, applied impulse voltage and gap length; For example, the E_{av} in the coaxial field is about half of the one in the uniform field at the gap length of 1 mm. With the increase of D, the difference of E_{av} between two types of electric fields is diminished and the decline of both E_{av} with D is also stabilized gradually. That two curves of E_{av} vs. D in Figure 9 approaches each other after surpassing a relatively greater gap length (> 4 mm under this experimental conditions , for example) reveals it is sensible to speculate on flashover voltage under coaxial field by the one under uniform field, which is valuable to the industrial designs of pulsed power equipments of coaxial structure.

4. Conclusions

The flashover voltage along the interfaces between nylon 1010/transformer oil increases nearly linearly with gap length under nanosecond pulsed coaxial electric field.

The composition effects of enhanced field strength at triple junctions, heightened nonuniformity degree of potential distribution over the interfaces between nylon 1010/ transformer oil and descended sharply field strength at the inner electrode surface make flashover voltage increase almost linearly with gap length whose increase would lead the coaxial field to tend to the very nonuniform field under point-plane electrodes.

Flashover natures are closely related to the electric field strength at triple junctions of solid-liquid-electrode and the potential distribution along the interfaces between different dielectrics. It is, in a general way, sure that the higher field strength at triple junctions and the more nonuniform potential distribution along the interfaces between different dielectrics would result in the lower flashover voltage, whereas in practice one should take all kinds of factors controlling flashover into account for correct results.

While gap length of coaxial electrodes is large enough, the average flashover field strength in coaxial field can be estimated by means of that in uniform field, which is rather significant to the design of coaxial structural pulsed power apparatus.

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