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CONCURRENT OPTICAL AND ELECTRICAL OBSERVATIONS OF THE 'SPONTANEOUS' SURFACE FLASHOVER OF SOLID INSULATORS IN VACUUM

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Abstract

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Concurrent optical and electrical observations of the 'spontaneous' surface flashover of solid insulators in vacuum

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Abstract. The performance of high-voltage solid insulators that are used to bridge vacuum gaps is frequently limited by surface flashover. An important characteristic of the flashover process under DC conditions is that it occurs 'spontaneously', namely without warning and any obvious external triggering agents. Significantly, this feature is not readily explained by the basic assumptions of the theoretical models that are currently used to explain the surface flashover mechanism. In an attempt to further our understanding of this observation, concurrent optical-electrical measurements were performed on standard truncated alumina ceramic cones. These studies have revealed that there are two important physical processes associated with spontaneous surface flashover events. The first has a clear origin at the cathode triple junction, whereas the second is associated with a micro-plasma that is initiated at two radially opposite points of the cathode and anode triple junctions. Two alternative physical mechanisms are proposed to explain the initiation of these two types of flashover event. Lastly, a novel physical description of the final phase of both types of flashover event is given.

1. Introduction

The surface flashover of solid insulators is the major limiting factor to the performance of many high-voltage vacuum devices and systems, and has recently been the subject of two complementary reviews by Miller [1] and Blaize and LeGressus [2]. Under DC conditions, the phenomenon either can be triggered by external agents [3] or can occur spontaneously [3,4]. This is illustrated, for example, by the behaviour of the ceramic insulators used in the separators of the Large Electron Positron Collider (LEP), for which it is found that sparks occur when the structures are bombarded by UV photons or electrons [3]. In spite of its technological importance, reports of experimental studies of the spontaneous flashover process have been relatively few. Equally, only a limited amount of theoretical attention has been paid to this phenomenon, with all existing models of the surface flashover phenomenon assuming that the process is initiated by an external triggering agent. The purpose of this paper is to investigate the physical origin of the spontaneous flashover phenomenon.

Our previous studies [5,6] have shown that luminescence from electrically stressed solid insulators is a key

signature both of the pre-breakdown and of the flashover processes. Furthermore, the pre-breakdown luminescence has been found to originate from solid state processes involving the recombination of conduction carriers with electron traps existing in the surface layer of the insulator; in contrast, the luminescence observed at the flashover stage is believed to be associated with plasma generation. Besides the above scientific findings, these earlier studies also demonstrated that the combination of an optical recording with a conventional electrical measurement record is a powerful diagnostic technique for characterizing both the pre-breakdown and the flashover phenomena. This technique was therefore a natural choice for this follow-up study.

2. Experimental methods

2.1. The system

In order to observe the optical activity associated with the pre-breakdown and surface flashover processes, an earlier 'transparent anode' imaging technique [3] was exploited to provide a window for making real-time dynamic studies of the evolutionary optical signature of these processes. Thus, referring to figure 1(a), a truncated cone ceramic

(a)

(b)

Figure 1. (a) The test electrode assembly, in which the vacuum gap is bridged by a solid truncated cone ceramic sample of 2 mm thickness. (b) An optical image showing the slanting surface of the sample (the white ring) and the smaller end face of the bulk of the sample (the darker central circular area).

sample is sandwiched between a metal base electrode and a three-element transparent anode electrode assembly. The latter consists of a metal tube that provides a support and electrical connection between a tin-oxide-coated glass disc and a large transparent anode. As can be seen from the reference optical image shown in figure 1(b), this design of the transparent anode assembly allows the direct and simultaneous observation of all optical activity that occurs both over the slanting surface and in the bulk of the ceramic insulating sample.

Figure 2 illustrates the experimental set-up used for concurrent optical and electrical measurements. In this, the high voltage is applied to the transparent anode electrode assembly, whilst the steady-state gap current is monitored using a pico-ammeter in series with the cathode electrode. The transient current pulses generated by flashover events occurring in the gap are detected by a simple wire loop wrapped around the EHT cable, followed by a discriminating stage and an in-house-designed amplifier unit. The output from this unit is then fed into a counter in

order to register the number of sparks that occurs during a fixed time period. The waveform of the detected signal was also displayed on the oscilloscope (Gould Advance Digital Storage Oscilloscope OS4000). With this arrangement, the magnitude of the detected pulse shown on the scope is always a good reference for judging whether or not the detected signal has been generated by a flashover spark. This same oscilloscope is also used for monitoring the gap voltage recorded from the output of a voltage divider connected in parallel with the gap.

Concurrently with initiating the above electrical measurement, a standard VHS video recording system is set running to monitor the progress of the experiment visually on a TV screen and to record all optical activity associated with the ceramic specimen. Subsequently, the recorded video film is subjected to a detailed analysis using the image analyser package 'ArcImage' of Foster Findlay.

2.2. The procedure

To ensure performance reliability, the truncated cone-shaped sample of alumina ceramic and all parts of the electrode assembly were cleaned in an ultrasonic bath for 15 min, and then left to dry. The electrode module was then assembled under clean conditions and mounted in the experimental vacuum chamber. Following an initial pumping down to $<10^{-7}$ Torr, the system was baked at 200 °C for 6 h, and allowed to cool down to room temperature before we commenced any experiment.

Starting with a virgin sample, an increasing external voltage was progressively applied across the ceramic sample in incremental steps of 500 V until it reached 30 kV, which was the maximum output of the EHT power supply. At each intermediate voltage, measurements were performed over a period of 1 min both of the mean steady state current flowing between the cathode and the anode, and of the number of sparks. Finally, the bridged gap was left for 50 min at its maximum operating voltage of 30 kV, during which the number of sparks, the optical activity associated with the sparks, and the location of their occurrence were recorded. In total, 50 samples were studied using this standard procedure.

2.3. Findings

The typical form of the stable inter-electrode current-voltage characteristic of the ceramic samples under investigation is shown in figure 3. It can be seen that it has a current threshold at around 15 kV, and a subsequent nonlinear region. The existence of a threshold indicates that a certain field strength is necessary to initiate the conduction process, whilst the nonlinear property of the $I-V$ curve could well indicate the existence of a strong space-charge effect. As will be more fully discussed later in section 4, the general nature of the $I-V$ characteristic is governed by (i) the injection of electrons across the metal-insulator cathode interface and (ii) their subsequent transport within the bulk of the insulator.

Two types of flashover event have been observed, where figure 4(a) shows a sequence of optical images

Figure 2. The experimental set-up.

Figure 3. A typical stable and nonlinear inter-electrode current-voltage characteristic recorded when no luminescence was observed.

associated with a type I event. It can be seen that the whole process starts with a luminescent centre localized at a point on the cathode triple junction (CTJ), which subsequently expands towards the anode to form a bright fan-shaped luminescent feature that is 'rooted' at the CTJ. This process is then followed by the dramatic optical event shown in the third frame of figure 4(a). We define this as a 'transient doughnut' event, because of its similarity in appearance to the 'doughnut luminescent effect' reported

in one of our earlier reports [6]. From this final image of the flashover process, it will be seen that the luminescence comes from the whole slanting surface, with the strongest photon emission appearing to stem from around the anode triple junction (ATJ). However, a 3D image analysis of this type of image has in fact shown that the light from the fan-shaped pattern is the most intense. With a frame speed of 25 frames per second, it was not possible to distinguish for certain whether the fan-shaped feature formed before

Figure 4. A typical type I flashover event. (a) A sequence of optical images showing how a luminescence centre is initiated at a cathode triple junction point, subsequently expands across the gap and finally leads to a flashover event. (b) The associated gap I - V characteristic observed with an electrometer.

Figure 5. A typical type II flashover event. (a) A sequence of optical images showing how a pair of luminescence point centres at the cathode and anode triple junctions expand to bridge the gap, precipitating a flashover event. (b) The associated gap I - V characteristic as observed with an electrometer.

or after the appearance of the total surface luminescence, although the evidence seems to indicate that the latter was triggered by the former. One important conclusion may, however, be drawn from this observation; namely, that, as assumed in our earlier model [5], a flashover event can be initiated at a CTJ.

Figure 4(b) illustrates the form of a typical I - t characteristic recorded under a constant gap voltage of 30 kV, and associated with the optical event shown in figure 4(a). Initially, under dark conditions, a low, stable and slowly varying pre-breakdown current flows across the gap. This pattern continues until the appearance of

Figure 6. A statistical summary, based on measurements on 50 specimens, of the incidence of the two types of flashover event recorded at 10 min intervals throughout a 50 min dwelling period at a constant applied gap voltage of 30 kV.

Figure 7. A statistical summary of the spatial distribution of flashover events over a 50 min dwell time at a constant applied gap voltage of 30 kV.

the first CTJ light spot, when the gap current exhibits a step-like transition from phase 1 (P1) to phase 2 (P2), thereafter increasing exponentially. Sometimes, such a gap current may dwell at P2 at an almost constant value for a variable period, say several minutes, during which one may observe many more frames of optical images similar to the second frame in figure 4(a). Finally, at a transition point between phases 2 and 3 (P3), the current shoots up to its breakdown value: this is a very quick process, occurring on a sub-microsecond time scale that was beyond the limiting time resolution of our oscilloscope. At this stage, it is also not possible to reveal whether this dramatic current increase happens before, after, or simultaneously with the luminescence recorded in frame 3 of figure 4(a).

A type II flashover event may be characterized with

reference to figure 5. Thus, as shown in frame 1 of figure 5(a), it starts with a pair of light spots appearing randomly at radially opposite points of the CTJ and ATJ. Sometimes they appear simultaneously, other times one after another, but in all cases they are associated with a transition of the gap current from a stable to an unstable state. The spots themselves are unstable, as manifested by their frequent and irregular changes in optical pattern and intensity. As shown in frame 2 of figure 5(a), their subsequent tendency is to expand with increasing time, which coincides with the increase in current illustrated in P2 of figure 5(b). This expansion process can take several seconds to reach the stage at which the two spots meet, to form the new pattern shown in frame 3 of figure 5(a). At this point the gap current increases rapidly, as shown in

Figure 8. Showing (I) equipotential and (II) field vector plots of the present experimental bridged vacuum gap with different surface charge densities, obtained from field plotting simulation.

Table 1. Experimental conditions and key findings. The surface charge density of electrodes is $+133 \times 10^{-6} \text{ C m}^{-2}$ for the top electrode and $-133 \times 10^{-6} \text{ C m}^{-2}$ for the bottom one. Applied voltages are: Top +30 kV, Bottom 0 V. Angle definition: with reference to the diagram, the axisymmetric geometry of the sample is such that the line $Z = 0$ is at an angle of 0° , for increasing R , whereas the line $R = 0$ is at an angle of $+90^\circ$, for increasing Z .

Simulation number	Charge density of sample surface (C m^{-3})	Top triple-point field magnification (M V^{-1})	Top triple-point field angle (degree)	Bottom triple-point field magnification (M V^{-1})	Bottom triple-point field angle (degree)
1	0	65.4	-20	2.8	-90
2	1	61.9	-20.2	3.4	-90
3	-1	68.8	-20.1	2.3	90
4	10	31	-21	8.3	-90
5	-10	99.7	-19.8	2.7	90
6	100	278	160.9	58	-90
7	-100	409	-19.4	52	90

P3 of figure 5(b), and continues to rise to its breakdown value as the 'transient doughnut' total surface luminescent phenomenon appears, as shown in frame 4 of figure 5(a) and region P4 of figure 5(b).

The frequency of occurrence of these two types of event is closely related to the history of the sample. In order to demonstrate this, figure 6 presents a statistical summary of the occurrence of the two types of flashover event during each 10 min interval over the 50 min dwell time at a constant applied gap voltage of 30 kV. It can be seen from figure 6 that type I events dominate the initial stage, but their frequency of occurrence decreases with increasing time. Type II events rarely occur within the initial 20 min, but gradually take over as the dominant process with increasing time.

There is also a difference in spatial distribution between the two types. Figure 7 gives a statistical summary of the distribution, and illustrates how type I events occur randomly everywhere, whilst type II events are more localized; in this particular example, in the bottom left-hand quadrant.

3. The field analysis

To help us understand the experimental findings presented in section 2.3, a field plotting exercise was carried out at CERN, using a program called Flux2D (Version 6.58). Due to the axial symmetry of the electrode configuration, both the potential and the electric field vector plots for the square

section of the specimen enclosed by the dotted line shown in figure 1(a) are sufficient for our present discussion.

Table 1 summarizes the experimental conditions and key findings of the simulation study. As can be seen from the first row of table 1, and frame I(a) of figure 8, when there is no trapped charge in the surface layer of the insulator, the geometry of the present gap results in a field enhancement at the ATJ, but a lowering of the field at the CTJ, i.e. as predicted by earlier authors [7]. Also, in frame II(a) of figure 8, it is important to note that the electric field vectors point to the surface of the insulator even though no trapped charges are assumed. Furthermore, this modelling has revealed that, when the sample surface charge density varies within the range $0-0.01 \text{ C m}^{-3}$, there is no significant change in the field distribution from that for the case of a non-charged surface layer. This conclusion is valid both for negative and for positive charge distributions.

To illustrate the effect of increasing the density both of positive and of negative charge, figures 8(b) and (c) presents the equipotential and field plots for charge densities of $\pm 10 \text{ C m}^{-3}$. From frame I(b) of figure 8, it can be seen that the positive charge results in a field at the CTJ that is slightly greater than that with the non-charged surface. It is also important to note from frame II(b) of figure 8 that the field direction on the surface varies significantly from the CTJ to the ATJ. For a negatively charged surface with a density of 10 C m^{-3} , frame I(c) of figure 8 shows that a new low-potential area exists in a region near to the CTJ, resulting in an inversion of field direction at the CTJ from that with the non-charged surface. An additional consequence of this is a greatly enhanced field at the ATJ.

4. Discussion

The findings presented in section 2.3 revealed that there are two types of flashover event, and that they seem to occur at different stages in the dwell time during which a bridged vacuum gap is first subjected to a constant high voltage. In the following section, we shall look into how the coherent set of concurrent optical and electrical measurements can help us to understand the physical processes involved in the two types of flashover event.

4.1. The evolution process of a type I flashover event

To aid the presentation of our understanding of the process, figure 9 illustrates schematically how the sequence of events develop, starting from (a), going through (b) and then to (c), using the combination of the transient current-time ($I-t$) characteristic assumed to occur in a flashover process (I), the conduction carrier distribution assumed to exist in the surface layer of an insulator (II) and the optical image (III).

Before the sequence is described, it is important to note several facts emerging from the experimental findings. As can be seen from figure 6, type I flashover events occur during the *early* phase of the 50 min dwelling period. At this early stage in the process, it can be assumed that insufficient time has elapsed for a significant amount of charge to have been trapped in the surface layer [8]; on the

Figure 9. A possible evolutionary model of the physical process associated with a type I flashover event.

other hand, a large number of vulnerable electron emission sites must exist at the CTJ.

Figure 10. A particle-based emission site at a cathode triple junction.

The proposed sequence of events in the evolution process will now be presented with reference to figure 9. As assumed in our earlier model [5], shallowly trapped residual charges will initially move under the influence of applied field and accumulate in the vicinity of both junctions, thus causing an enhancement of the local field. This process can be assumed to create the conditions for the spontaneous switching on of a particle-based electron emission site [9] at the CTJ. With reference to figure 10, such a particle can exist at a point of the CTJ, either embedded within or sitting upon the surface of the cathode. When the switching on occurs, electrons will be emitted in a burst of current (see frame I(a) of figure 9), as shown in our earlier work [9]. The emitted electrons will be injected into the surface layer of the insulator sample, with the spread of angles illustrated in frame II(a) of figure 9. Indeed, it is the scattering of these latter electrons that results in the appearance of the first light spot at the CTJ illustrated in frame III(a) of figure 9.

Subsequently, the emission will continue to rise rapidly, as illustrated in frame I(b) of figure 9, and the charge injected into the surface layer will be 'internally' transported towards the anode under the influence of the applied field. Since this process will be a space-charge-limited one [10], the only way that the rapidly increasing emission current can be accelerated in the insulator is for the carriers to spread out in space, namely to form the fan-shaped image illustrated in frames II(b) and III(b) of figure 9. At first glance, one might assume that the next step of the process would be the breakdown of the emission site, as in a vacuum gap [9]. However, our calculations show that, in fact, the voltage across the gap has virtually collapsed when the current approaches about 2–3 mA, since, under these conditions, most of the gap voltage is dropped across the 10 M Ω resistor in series with the gap. Thus, in contrast to the mechanism proposed by Cross [4], there is no need in our model to assume explosive emission from a cathode site. As the emission rises further (see frame I(c) of figure 9), the spatial expansion of the conduction electrons carries on, as illustrated in frame II(c), leading eventually to the large fan-shaped optical image illustrated in frame III(c) of figure 9. This is followed by the 'transient doughnut' event shown in frame 3 of figure 4, which will be discussed in detail later in section 4.3.

4.2. The evolution process of a type II flashover event

As with type I events, the process associated with type II flashover events is again assumed to be initiated by electron emission from a particle-based site on the cathode surface,

Figure 11. A possible evolutionary model of the physical process associated with a type II flashover event.

as illustrated in figure 10. In this case, however, two new factors have to be taken into account: (i) many emission

Figure 12. Possible physical processes that could give rise to luminescence over the whole insulator surface.

sites will already have been switched on, so that instead of the resulting emission having the transient nature described in the last section, it will rather increase slowly as illustrated in frame I(a) of figure 11, and (ii) the emitted electrons are more likely to be expelled into the vacuum by the negative charge trapped in the surface [8]. Consequently, no bright light spot was initially observed at the CTJ.

Since the same negative space charge in the surface will also prevent vacuum electrons from striking the surface, it follows that the emitted electrons will be accelerated towards the ATJ, as illustrated in frame II(a) of figure 11. The resulting bombardment of the metal anode by these vacuum electrons, having energies of about 30 keV, will generate local desorption, ionize desorped species and thereby create the observed anode hot spots illustrated in frame III(a) of figure 11. Furthermore, the positive ions emitted from this region will be accelerated back towards the negatively charged surface and the CTJ, as illustrated in frame II(a) of figure 11. Thus, those ions that interact with the surface will lead to a decrease of negative surface charge density, whilst those that impact near the 'primary' electron emission site will give rise to a subsequent enhancement of the local field and a consequent increase in the emission, as illustrated in frame I(b) of figure 11. As happens in a vacuum gap, the increase in electron emission will result both in the appearance of a cathode spot, as shown in frame II(b) of figure 11, and in a more intense bombardment of the ATJ, as illustrated in frames II(b) of figure 11. In addition, if the surface inverts to being positively charged, vacuum electrons will also strike the surrounding area of the ATJ, as predicted by the field plotting result shown in frame II(b) of figure 8.

The regenerative process described above will finally lead to an expansion of the local plasmas associated both with the anode spots and with the cathode spots, indicated initially by the increase in emission current illustrated in frame I(c) of figure 11. The electrical breakdown of the gap will thus occur when these two plasmas meet each other, as illustrated in frame III(c) of figure 11. This is followed by a final 'transient doughnut' event shown in frame 4 of figure 5 when photons are emitted from almost

the whole of the slanting surface of the insulator. As will be described below, it is our belief that the physical process responsible for this final event has much in common with that of the type I process described above.

4.3. The 'transient doughnut'

In the above discussion, it has been assumed that the electrical breakdown of a bridged vacuum gap actually occurs as a result of a localized conduction process. However, the most important feature of our model is the novel description of the physical processes associated with the 'transient doughnut' events, shown in frame 3 of figure 4 and frame 4 of figure 5.

It is believed that this phenomenon is a consequence of the relaxation of polarization. Thus, before the gap collapses, the applied field E_a , the polarization P and the total field E will be as illustrated in figure 12. With the sudden collapse of the gap (after a few nanoseconds), the applied field is very quickly removed and, as a result, the polarization P will be removed within microseconds [11] of the time that the collapse occurs. As discussed elsewhere by Blaize and LeGressus [2], such a process will lead to the release of the polarization-based mechanical energy stored in the ceramic sample and its subsequent conversion into heat [11], such that the local energy density released in this process is a function of the rate of change in local polarization. Due to the existence of trapped charges, the change in the polarization in the surface layer can be anticipated to be greater than that in bulk, so that the locally released energy density in the surface layer should be higher. Consequently, heating in the surface will be greater than in the bulk, thus favouring the occurrence of a surface flashover event. Indeed, calculations of the magnitude of this effect indicate that localized temperature excursions can be sufficient for plasma generation [2].

As pointed out by Mott *et al* [12], an increase in temperature will also enhance the probability of the hopping of trapped charge. Thus, polarization relaxation will be directly responsible for the release of charge trapped in the surface layer. Under the influence of the remaining

gap field, the de-trapped charges move towards the anode to create the observed gap currents, whilst the re-trapping of the charges will result in photon emission. Since this process is not localized, luminescence from the whole slanting surface is observed.

5. Conclusion

An existing 'transparent anode' optical imaging technique, in conjunction with traditional electrical measurement methods, has successfully been adapted for a systematic study of the spontaneous flashover phenomenon associated with a conical insulator structure systematically. From the findings of this experimental study, the following conclusions may be drawn.

(i) A flashover event is initiated by electron emission from a point at the cathode triple junction.

(ii) There are two distinct types of spontaneous flashover event. Apart from having different optical signatures, they are characterized by their occurrence at different stages during the initial dwell time when a constant high voltage is first applied to an alumina sample.

(iii) Both types of flashover event have a common final stage manifested as a 'transient doughnut' pulse of optical emission from the whole insulator sample.

Apart from proposing a novel physical interpretation of this 'transient doughnut' phenomenon, this study has been able to provide a qualitative account of the observed characteristics of the recorded events.

On the basis of these findings, future experimental work should focus on the following two major directions.

(i) Spectral characterization of the 'colour' of the luminescence associated both with the pre-breakdown and with the flashover phenomena should be attempted.

(ii) An improved time-resolved sequence of evolutionary optical images of the developing flashover process should be obtained. This objective is particularly important since it would confirm, or otherwise, the fundamental

assumption of the proposed models that the observed optical pre-breakdown processes are spatially correlated with the initiation of the flashover event.

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