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Electrical breakdown of mineral oil under non-uniform fields

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Abstract. The dependence of the direct electrical breakdown voltage of degassed transformer oil and of gas-saturated oil on gap length for a point–sphere electrode system has been studied for the two polarities of the point. The effects of anodization of the sphere electrode on the breakdown voltage against gap characteristics have also been examined. The critical gap length at which the breakdown voltage is the same for both polarities of the point has been found to depend on the nature of the insulating film on the sphere electrode and on the type of gas dissolved in the oil. The discussion of the results is based on the propagation of a corona discharge from the point electrode and the possibility of formation of a back streamer from the sphere electrode.

1. Introduction

Work on the breakdown voltage of liquid insulants using point-to-plane or point-to-sphere electrode geometries has shown that there exists a marked polarity effect. Some workers have found that the breakdown voltage is higher for a positive point polarity whereas others found that a negative point gave higher breakdown voltages. This apparent contradiction in the results has been explained by the actual existence of a crossover point in the breakdown voltage against gap length characteristics (Zaky and Hawley 1973). This crossover point corresponds to a critical gap length at which the breakdown voltage is the same for both polarities. At larger gaps, a negative point polarity gives the higher breakdown voltage whereas for smaller gaps the breakdown voltage is higher for a positive point polarity. It has been suggested (Gosling and Tropper 1964) that the existence of a critical gap length is associated with the extent to which a discharge, initiated at the point cathode, propagates into the gap before being quenched. Preliminary results by the present authors indicated that the critical gap length does not depend on the electrode material (Zaky *et al* 1976) but is dependent on the surface state of the sphere electrode and on the presence of dissolved gas in the oil (Evangelou *et al* 1975, Zaky *et al* 1976). Recent work on corona discharges in insulating liquids using point electrodes suggests that both the initiation and propagation of the discharge depend on the gap length (Singh *et al* 1972, Shammas *et al* 1974, Takahashi and Ohtsuka 1975).

The present paper gives the results obtained from an investigation of the effect of gap length on the breakdown voltage of mineral oil using point–sphere electrodes. The influence of the surface state of the aluminium sphere electrode and of gases dissolved in the oil on the polarity dependence of the breakdown voltage has been extensively examined and an account is given of the physical processes which are believed to be responsible for the experimental observations reported.

2. Experimental procedure

The tests were carried out on transformer oil (Shell Diala B) complying with BS 148 : 1959. The oil samples were degassed at a pressure of 10^{-2} Torr and filtered through a 0·5 μm Millipore filter. To investigate the effect of dissolved gases, the dried and filtered gas was allowed to bubble slowly into the degassed liquid which then remained in contact with the gas at atmospheric pressure for 16 h. Tests on both degassed and gas-saturated oil samples were carried out at atmospheric pressure.

A nickel-plated steel sewing needle of tip radius 25 μm was used as the point electrode. The other electrode was a 5 mm diameter aluminium sphere. The electrodes were mounted horizontally in the test cell. To determine the effect on the breakdown voltage of the presence of a strongly insulating barrier on the sphere electrode, the spheres used in the tests were either etched or etched and then anodized. The technique used for electrode preparation as well as breakdown measurements has been described elsewhere (Evangelou *et al* 1975). Direct voltages and a diverter circuit were used in all tests. Each breakdown voltage reported was the average of 20 breakdowns; the coefficient of variation varied between 5 and 11 %. New electrodes and fresh liquid samples were used for each gap setting.

3. Experimental results

Figure 1(*a*) shows the relationship between the gap length and the breakdown voltage for degassed oil for both polarities of the point electrode and an etched sphere electrode. The characteristics clearly indicate a polarity effect with a crossover point corresponding to a gap length of 325 μm. This value is in good agreement with that of 300 μm predicted by Angerer (1965) for degassed transformer oil.

The breakdown voltage against gap length characteristics for both point polarities and degassed oil but with an anodized sphere electrode are shown in figure 1(*b*). Here

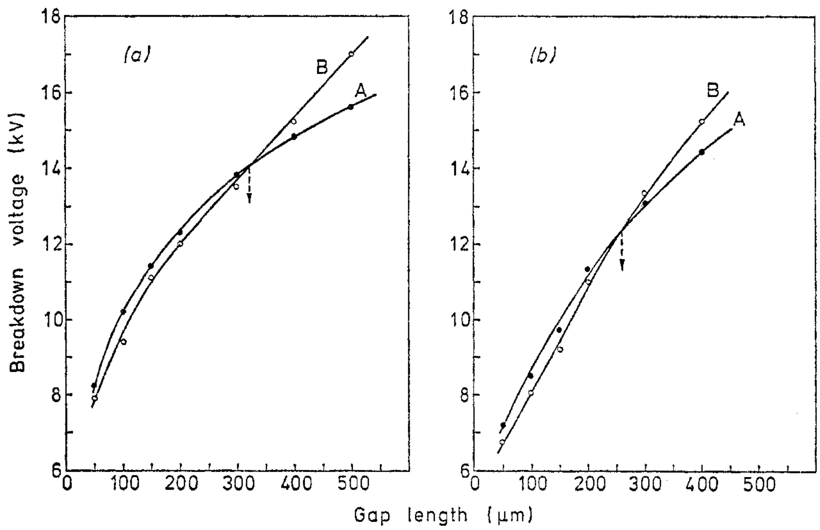

Figure 1. Breakdown voltage versus gap length for degassed oil. Sphere electrode: (*a*) etched; (*b*) anodized. A, point positive; B, point negative.

the crossover point occurred at a gap length of about 265 μm. With the sphere anodized and for gap lengths less than about 300 μm there is an appreciable reduction in the breakdown voltages for both point polarities as compared with the corresponding breakdown voltages with an etched sphere.

The breakdown voltage versus gap length characteristics for oil saturated with oxygen are given in figure 2(*a*) for an etched sphere electrode and in figure 2(*b*) for an anodized sphere electrode. In both cases the breakdown voltage is higher with the point negative than with the point positive over the whole range of gap lengths examined. It would appear that the crossover point in both cases is shifted to a gap length of less than 50 μm.

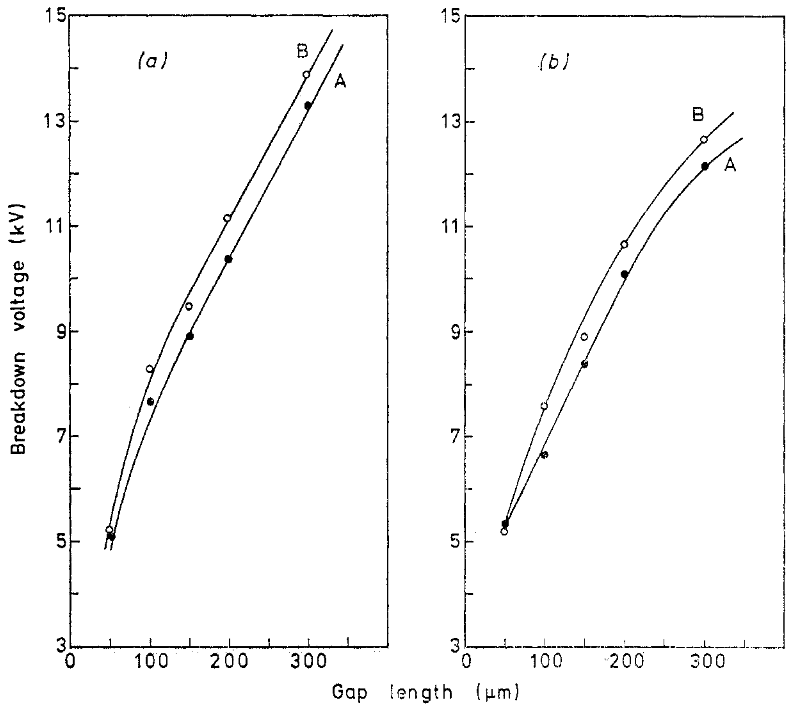

Figure 2. Breakdown voltage versus gap length for oil saturated with oxygen. Sphere electrode: (*a*) etched; (*b*) anodized. A, point positive; B, point negative.

The results obtained for oil saturated with nitrogen are given in figure 3(*a*) and (*b*). A polarity effect is again evident for both surface states of the sphere electrodes. Comparison of these results with those obtained for degassed oil indicates that the presence of nitrogen produced a considerable reduction in the crossover length. However, contrary to the degassed example, the crossover gap length (100 μm) was unaffected by anodization of the sphere electrode. The breakdown voltage levels were similar to those obtained for oxygen-saturated oil but were considerably lower than those obtained for degassed oil.

Table 1 summarizes the values of the crossover gap lengths obtained under different test conditions.

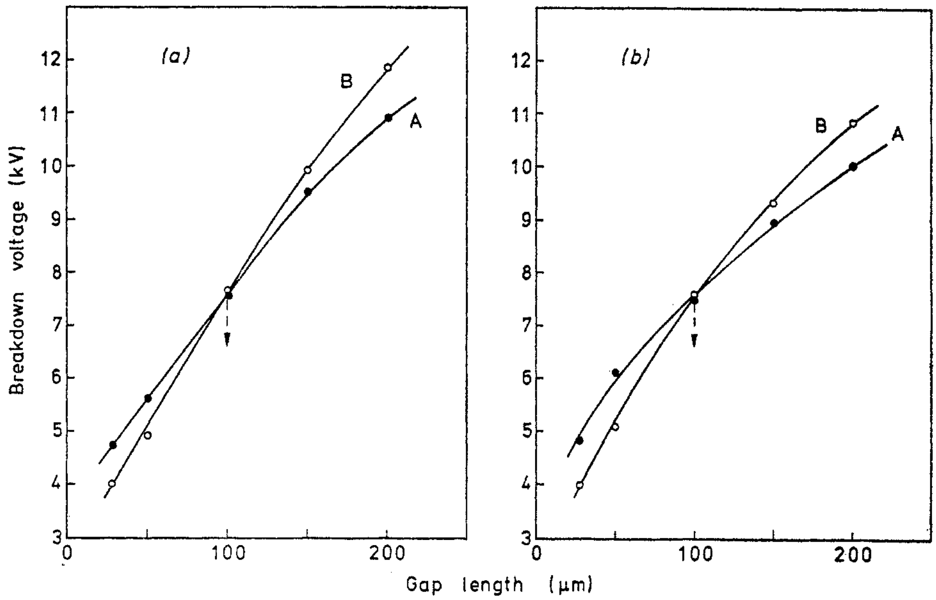

Figure 3. Breakdown voltage versus gap length for oil saturated with nitrogen. Sphere electrode: (*a*) etched; (*b*) anodized. A, point positive; B, point negative.

Table 1. Crossover gap lengths (μm) for different test conditions

Oil	Etched sphere	Anodized sphere
Degassed	325	265
O_2-saturated	< 50	< 50
N_2-saturated	100	100
Air-saturated (Evangelou *et al* 1975)	266	158

4. Discussion

For highly non-uniform point–sphere field geometries, breakdown is always preceded by the onset of corona, accompanied by the formation of bubbles at the point electrode (Singh *et al* 1972, Sibillot and Coelho 1974, Takahashi and Ohtsuka 1975). Such corona is a localized discharge phenomenon the occurrence of which need not necessarily lead to a complete breakdown of the gap. Corona may also form at localized high-field sites (protrusions) on the surface of the sphere electrode. After initiation, the extent to which a corona discharge propagates into the gap will increase with increasing voltage (Chadband *et al* 1971, Shammas *et al* 1974). Breakdown will occur when such a discharge bridges the gap. The factors affecting the initiation and propagation of the discharge will be discussed in the light of the present results.

4.1. *Effect of gap length*

4.1.1. Degassed liquid. At large gaps the corona discharge from the point electrode will not bridge the entire gap. The final bridging of the gap (breakdown) will be triggered by a streamer initiated at the sphere electrode and travelling back towards the corona region (Stekolnikov and Ushakov 1960, Fiebig 1969). Such a streamer will propagate into a region of increasing field. One would expect that a back streamer would be more readily initiated at a sphere cathode because of the presence of local emitting sites at which the field is further enhanced by the presence of unneutralized positive ions. This would explain the lower breakdown voltages observed for positive points at large gaps.

At small gap spacings, the corona at the point electrode would propagate and bridge the gap. Since a positive point has a higher corona inception voltage than a negative one (Takahashi and Ohtsuka 1975), a positive point should give a higher breakdown voltage than a negative one. Therefore, the superposed breakdown voltage against gap characteristics for both point polarities will exhibit a crossover point corresponding to a critical gap length.

4.1.2. Gas-saturated liquid. For oil saturated with oxygen, the results indicate that there is a considerable reduction in the critical gap length to gaps smaller than 50 μm (table 1). This may be attributed to the strong electron-trapping properties of oxygen which will inhibit the propagation of the discharge from the point cathode.

It would appear from the results that dissolved nitrogen also has a quenching effect since there is a marked reduction in the crossover point compared with the degassed oil. This effect, however, is less pronounced than that for oil saturated with oxygen. Recent work (Nosseir 1975) has shown that nitrogen dissolved in oil reduced conduction currents as well as current pulses.

4.2. Effect of anodization on the breakdown voltage

In order to compare the breakdown characteristics for a given point polarity under different test conditions, the results are replotted in figure 4(*a*) for the point negative and in figure 4(*b*) for the point positive.

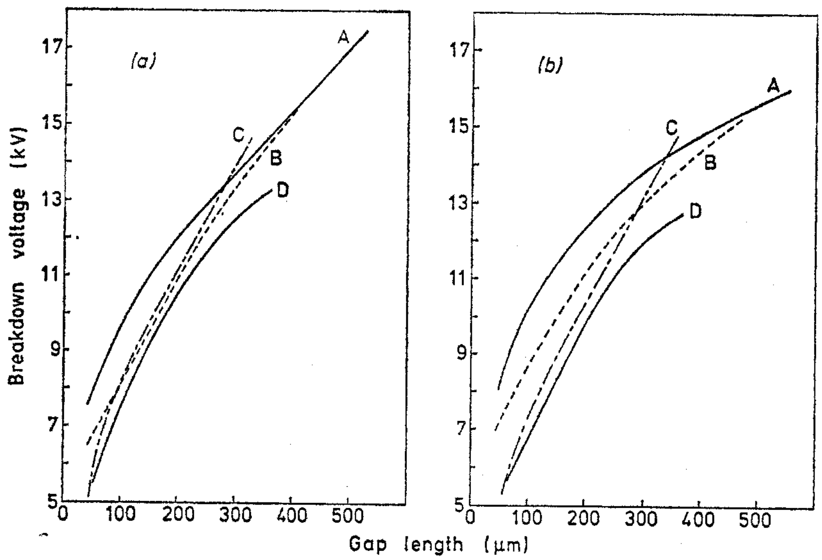

Figure 4. Breakdown voltage versus gap length for (*a*) a negative point, (*b*) a positive point. A, degassed oil, sphere etched; B, degassed oil, sphere anodized; C, oil saturated with oxygen, sphere etched; D, oil saturated with oxygen, sphere anodized.

4.2.1. Degassed liquid. A general feature of the results is that anodization of the sphere electrode had little effect on the breakdown voltage at large gaps (curve B, figure 4(*a*) and (*b*)). This is because the breakdown voltage in liquid insulants is governed by electrode surface effects and by bulk liquid effects. Electrode surface effects predominate at small gaps whereas at large gaps they will be masked by the bulk liquid effects.

When the point is negative the results show that anodization of the sphere anode resulted in a marked reduction in the breakdown voltage at small gap spacings. The presence of an insulating film on the anode lowers the breakdown strength of liquid insulants (Zaky and Hawley 1973) for uniform field geometries. In the present case it is suggested that unneutralized positive ions enhance the local field at the anode thereby facilitating the initiation of a back streamer which will propagate towards the point cathode.

When the point is positive, because of the high field in its vicinity, positive ions will be formed as a result of electron stripping from liquid molecules. These ions will be driven towards the sphere cathode; the presence of an oxide film on the surface of that electrode will hinder their immediate neutralization. Hence a positive space charge will form at the sphere cathode and intensify the field across the insulating layer. Electro-formed insulating oxide films are known to be efficient electron emitters. The mechanism of emission depends on the film thickness (Guile and Hitchcock 1975). For thin films emission is by electron tunnelling from the cathode substrate, whereas for thick films emission is mainly from electroforming of conducting filaments through the film as a result of the intense field set up by positive charges. For the same number of positive ions, emission from thick films will be greater than that from thin ones. Thus the observed reduction in the breakdown voltage of the degassed oil when using an anodized sphere cathode, as compared with an etched cathode, may be attributed to the increased electron emission.

4.2.2. Liquid saturated with oxygen. The results show that with the sphere etched, the presence of dissolved oxygen reduced the breakdown voltage for small gaps but increased it for large ones (curve C, figure 4(*a*) and (*b*)). This is because dissolved oxygen has a harmful as well as a beneficial effect.

In a highly stressed gap the liquid is set into motion; such motion increases with increasing field. As a result of this motion gases will tend to come out of solution in the form of bubbles. Thus for highly non-uniform fields microbubbles will form more readily in the vicinity of the point electrode. In effect, Mirza *et al* (1970) have observed that for highly non-uniform fields liquid motion occurred in the form of a jet accompanied by a spray of bubbles directed away from the point electrode. The formation of these bubbles, which is accompanied by corona, may explain the observed reduction in the breakdown voltage at small gaps. For large gaps, however, the generation of bubbles and corona formation will be localized at the point electrode and will not necessarily lead to a complete bridging of the gap. Moreover, the beneficial electron-trapping properties of oxygen would have an inhibiting action on the propagation of the discharge channel and this would lead to an increase in the breakdown voltage.

With an anodized sphere electrode, dissolved oxygen reduced the breakdown voltage for all gaps as compared with the degassed liquid (curve D, figure 4(*a*) and (*b*)). This may be attributed to the fact that when the sphere is anodized, the field intensification by space charges at that electrode would facilitate the initiation of a back streamer, as discussed in §4.1, thereby lowering the breakdown voltage.

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