Positive Breakdown Mechanism in Transformer Oil Subjected to a Non-Uniform DC Field

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Using a slowly rising DC voltage, the rapid current increase at a critical voltage and the breakdown voltage were measured in transformer oil with needle- or blade-plane geometries. The mechanism of the onset of positive breakdown was studied using experimental and computed results. The computation showed that the local field strength on the planar surface is increased very much by the space charge effect in accordance with the influence of liquid motion. This leads to the generation of new charges in front of the planar surface; the charges drift towards the sharp electrode tip. Consequently, it is suggested that partial discharge at the tip is initiated; a positive streamer then starts from the tip, and breakdown ensues. The generation of new charges is confirmed not only by the dust figure method but also by the signal pulse induced on the probe.

Key words: Transformer oil, Charge injection, Positive breakdown mechanism, Dust figure, Liquid motion

1. Introduction

High-voltage impulses have been frequently used when investigating breakdown phenomena in dielectric liquids; prebreakdown disturbances propagating from sharp electrodes have been reported⁽¹⁾⁽²⁾. The mechanism causing impulse breakdown in liquids is thought to be mainly connected to a time lag in the breakdown process. This mechanism is initiated by the appearance of electrons coming from the cathode; these electrons are the primary factor of the breakdown⁽³⁾. Furthermore, it has been reported that the time lag for needles at a positive potential is shorter than that for those at a negative potential; also, the propagation speed of a positive streamer is faster than that of a negative one⁽⁴⁾. In these cases, liquid motion, however, can play no role in the impulse breakdown since the onset of electrohydrodynamic (EHD) movement is not fast enough⁽⁵⁾.

In liquids under high DC stresses, when EHD motion is inevitably established in regions where a

gap exists, the electric field distribution in the gap will be changed drastically in comparison with that under impulse stress. As for the mechanism of DC breakdown, several researchers have pointed out the following factors. Kao has reported that the generation of bubbles due to Joule heating is the cause of breakdown and that the impact ionization process in liquids is contradictory⁽⁶⁾. In recent years, Wintenberg, et al.⁽⁷⁾, Denat, et al.⁽⁸⁾, and Marsden, et al.⁽⁹⁾, after studying current bursts due to partial discharges in dielectric liquids subjected to DC stresses, have reported that partial discharge currents in the liquid phase add to a condition that can lead to breakdown. On the other hand, Bragg, et al.⁽¹⁰⁾ and Swan, et al.⁽¹¹⁾, after considering the effect of space charge on the field strength, have reported that the field existing on the surface of a cathode or an anode is the principal factor of breakdown. In their papers, however, the effect of liquid motion was not treated appropriately.

In this paper, the phenomena of rapid current increase and voltage breakdown under a slowly

rising DC voltage were measured in transformer oil using needle- and blade-plane geometries. In addition, the electric field in the gap at a voltage close to positive breakdown was computed by taking into account both liquid motion and space charge. A new mechanism for the onset of positive breakdown is proposed and discussed on the basis of the experimental and computed results.

2. Experiments and Results

2.1 Experimental setup

Fig. 1(a) shows the experimental setup. Needle- and blade-plane geometries were used to apply DC stresses to a commercial transformer oil (JIS C-

(a) Experimental setup.

(b) Schematic diagram of the electrode systems: d denotes the gap spacing, r_n the needle electrode tip radius, r_b the edge curvature radius of the blade electrode and L the blade electrode length.

Fig. 1. Experimental setup and electrode systems.

2320). The oil was filtered through a $5\text{ }\mu\text{m}$ sintered glass filter and introduced into a metal test cell having three quartz windows. Fig. 1(b) shows a schematic diagram of the two electrode configurations. Needle electrodes were made of platinum wire etched to various tip radii r_n of less than $20\text{ }\mu\text{m}$. Blade electrodes were made of thin stainless steel with a maximum length L of 33 mm ; the radius of the edge curvature r_b was about $15\text{ }\mu\text{m}$. The planar electrode was made of a polished stainless steel disc, 50 mm in diameter, having an electrode edge with Rogowsky profile. The maximum gap spacing d was 6 mm .

The present study was devoted to measurements of the rapidly increasing current above a critical voltage, the velocity of the EHD flow and the breakdown voltage. The liquid velocity measurement near positive breakdown was performed with a laser-Doppler velocimeter (LDV). The characteristics of the LDV and the experimental procedure were the same as that described in a previous paper⁽¹²⁾. The breakdown was confirmed by a spark of light in the gap. The breakdown voltages were measured about 20 times for each electrode geometry; high voltage electrodes were replaced after every breakdown.

2.2 Rapid increase of conduction current and flow velocity of liquid

Fig. 2 shows typical current-voltage (I - V) curves. The current showed quasiohmic behaviour at low applied voltage. This is regarded as a dark current created by electrolytic dissociation of impurities present in the liquid; it increased with increases in emitting area of the sharp electrode tips. Above a critical voltage V_c , the current increased rapidly. This increase can be explained by the onset of carrier injection into the liquid; the case of sharp electrodes at a negative potential, the rapid increase of current is due to field emission, and with positive ones, it is due to field ionization⁽¹³⁾. Assuming that a current of $10^{-11} \sim 10^{-10}\text{ A}$ below V_c does not affect the electric field, the field strength E_{ct} on the tip surface at V_c is calculated by the Charge Simulation Method (CSM). Fig. 3 shows E_{ct} computed from experimental V_c . The E_{ct} decreased with increasing r_n and L . This decrease can be explained by the

(a) Needle-plane geometry.

(b) Blade-plane geometry.

d denotes the gap spacing, r_n the needle tip radius and L the blade length.

Fig. 2. Typical current-voltage curves.

(a) Needle-plane geometry.

(b) Blade-plane geometry.

Fig. 3. Field strength E_{ct} on the tip surface at V_c .

apparent decrease in the work function of metal immersed in a liquid medium as shown by Yamashita, et al.⁽¹⁴⁾. It has been reported that the effective work function of metal in a liquid is smaller than that of metal in a vacuum⁽¹⁴⁾⁽¹⁵⁾. The work function Φ_e of metallic sharp electrodes at a negative potential in transformer oil was examined. The currents from 10^{-11} to 10^{-8} A fit Schottky plots (linear plot of $\log I$ vs. $V^{1/2}$), as shown in Fig. 4. The Φ_e for Schottky emission is given by

$$\Phi_e = 1.42 \times 10^{19} kT \log(CT^2 S_0 / I_0) \quad (\text{eV}) \quad (1)$$

where k denotes the Boltzmann's constant in Joule/K; T the temperature (293 K); S_0 the emitting area in m^2 , which is assumed to be $0.6\pi r_n^2$ for the needle and $0.6\pi r_n L$ for the blade⁽¹⁶⁾; C a constant (usually $C = 1.2 \times 10^6 \text{ A/m}^2 \text{K}^2$); and I_0 the apparent current at $V^{1/2} = 0$, which is obtained from the

Fig. 4. Typical results of the Schottky plot.

Table 1. Effective work function of metal in transformer oil.

Work function (eV)	Needle tip radius r_n (μm) (Metal: Platinum)			Blade length L (mm) (Metal: Stainless steel)				
	4	10	20	0.05	0.3	1.0	8.25	33.0
ϕ_e	1.271	1.260	1.255	1.20	1.18	1.15	1.12	1.06
ϕ_v	5.32							

ϕ_e : effective work function for transformer oil

ϕ_v : work function of metal in vacuum

intercept of the extended Schottky plot. Table 1 shows the value of ϕ_e obtained by curve fitting. The ϕ_e for needle and blade geometries both decrease as r_n and L increase, respectively. The work function ϕ_v of stainless steel in vacuum could not be determined.

Concerning the I - V characteristics in dielectric liquids, it has been reported that the values of V_c in the case of field ionization in saturated hydrocarbons or some cryogenic liquids are higher than those in the case of field emission⁽¹³⁾⁽¹⁷⁾. Schnabel, et al.⁽¹⁸⁾ also studied the field ionization of aromatic liquids; they reported that the relation between I and V for field ionization showed the same dependence as the

 Fig. 5. Typical distributions of flow velocity U .

one for field emission. In our experiments, the I - V curves for negative and positive applied voltages approached the same values (Fig. 2), which coincides with the results of Schnabel, et al.⁽¹⁸⁾. The transformer oil used is composed of paraffinic compounds (50%), naphthenic compounds (37%) and aromatic compounds (13%). The aromatic compounds are sensitive to field ionization because of their relatively low ionization potential. Thus, the positive V_c will be reduced to values near the negative V_c . In these cases, the current must be sustained

(a) Needle-plane geometry.

(b) Blade-plane geometry.

Fig. 6. Polarity effects on breakdown voltage V_b .

by ions since no free electrons can exist.

The injected charges drift towards the planar electrode; in addition, there is a liquid flow from the sharp electrode towards the plane whatever the polarity of applied voltage⁽¹²⁾. Fig. 5 shows the distribution of flow velocity (measured with the LDV) under a positive voltage close to breakdown. The velocity at V_c is also shown in Fig. 5.

2.3 Electron emission from the planar electrode just before breakdown

In the case of a slowly increasing voltage, the negative breakdown voltage was much higher than the positive one for each electrode geometry, as shown in Fig. 6. In the negative needle case, Wintenberg, et al.⁽⁷⁾ have determined from measurements of current bursts that an expansion of the low-density region near the tip due to the partial discharge is the dominant cause of precipitate breakdown. In the positive needle case, the partial discharge region was generally not well defined⁽⁹⁾.

In the present study, it was found by the following two methods that a second charge generation from the planar electrode occurs at a voltage close to the breakdown in the positive needle case.

(1) Charge on the planar electrode detected by dust figures

In order to verify the injection of charge from the planar electrode and its polarity prior to the breakdown, a dust figure method was used. In tests of the needle-plane geometry with a gap spacing $d=4$ mm,

Fig. 7. Typical dust figures obtained for a positive needle-plane geometry with $d=4$ mm and $r_n=10$ μ m.

firstly, a charge-free dry insulator film (polyester plate), thickness 0.2 mm, was fixed on the planar electrode in the test cell; then, transformer oil was introduced into the cell. Secondly, after imposing a DC voltage on the needle, the voltage was removed and the insulator film was taken carefully out of test liquid. Then a mixture of sulphur and red lead powder (red lead 5% and sulphur 95%), which is ground into charged powder, was sprinkled over the film. Thirdly, the insulator film was washed very carefully in gasoline, and then the surplus powder was swept away leaving a dust figure.

Fig. 7 shows typical dust figures obtained with positive needles before the breakdown. At low voltages ($V < 20$ kV), positive charges accumulated on

the insulating plate as shown in Fig. 7(a); that is, only sulphur powder adhered to the plate. At higher voltages ($V=28$ kV), negative charges appeared within a restricted area directly under the needle electrode as shown in Fig. 7(b); that is, red lead remained in the central area. Similar results were also found in the case of positive blades. These dust figures confirmed that cations were injected from sharp electrodes and that anions appeared in front of the planar electrode under positive voltages close to breakdown.

(2) Signal pulse induced on the probe due to a charge emission from the planar surface

In the case of positive needles, the dust figures suggest that electrons are emitted from the planar surface at voltages close to the breakdown. Some of the electrons will be neutralized by cations emitted from the needle tip; the remaining electrons turn into anions and drift towards the needle tip under the effect of both the liquid motion and the Coulomb force. In order to confirm the anion drift, an open-loop probe was inserted into the flow as shown in Fig. 8(a). Signal pulses were obtained for several

tens of ms before the breakdown, as shown in Fig. 8(b). These signals differ from the ones induced by the prebreakdown current from the tip, which occur several μ s before the breakdown. Thus, it was confirmed that charges emitted from the planar surface can drift towards the needle electrode. In Fig. 8(b), there exist some elementary oscillations and each of them consists of a pair of succeeding half waves, the first positive and the second negative. The response of the probe in the measuring system was tested in the air by a negative charge approaching to and departing from the probe; the storage memory oscillograph showed the elementary oscillation similar to the first oscillatory part of Fig. 8(b). Consequently, Fig. 8(b) shows that several groups of anions emitted from the planar surface pass over the probe and then a breakdown is caused.

3. Considerations

3.1 Positive field strength close to the breakdown voltage

In transformer oil which experiences violent liquid motion at voltages close to the positive breakdown, the distributions of field strength affected by the space charge in the gap were obtained from numerical analyses. The incompressible liquid flow was analyzed using the Navier-Stokes equation and the continuity equation⁽¹⁹⁾⁽²⁰⁾. It is necessary to know the distribution of space charge density q in C/m³ and the electric field strength E in V/m since the liquid motion originates from the Coulomb force $qE dv^{(21)}$, where v denotes the volume in m³. If q is known, E can be calculated by the CSM. In this study, a hypothetical charge pillar with a cross-sectional area S in m² is assumed to lie along the axis (or the plane) of symmetry of the electrode geometry, and q is deduced from $q \approx I/(US)^{(19)(21)}$, where I denotes the conduction current and U the liquid velocity. The numerical method of calculating the liquid motion induced by the Coulomb force was almost the same as that described in a previous paper⁽¹⁹⁾, except for the reasonable assumption that the area S is a function of the distance between the electrodes in order to fit the experimental data of liquid velocity shown in Fig. 5.

Fig. 8. An example of signal pulses caused by the transit of anions.

Fig. 9 shows the electric field strength E along the axis, calculated for a voltage close to positive breakdown. The dotted curves represent the electric field strength E_0 for the charge-free case at the same voltage. Near the sharp electrode, E is lower than E_0 ; however, it is much higher than E_0 in front of the planar electrode. Such field distributions indicate that a positive space charge was injected by the sharp electrode; therefore, the injection will be space-charge limited. The injected charges drift continuously towards the planar electrode due to the effect of the Coulomb force and the liquid flow, so that E in the vicinity of the planar electrode is increased by the space-charge effect. The field strength for the negative critical voltage V_c ($V_c = -3$ kV for the needle and $V_c = -5$ kV for the blade) is also shown in Fig. 9. From this calculation, the following relationships result among the field strengths of the electrode surfaces: the field strength E_p of the planar surface is approximately equal to the field strength E_{ct} on the blade tip at V_c ; namely, $E_{ct} \approx 12$ MV/m for the blade at $V_c = -5$

kV, $E_p \approx 13$ MV/m for the blade at $V = 23$ kV and $E_p \approx 15$ MV/m for the needle at $V = 16$ kV. According to both the field calculation and the experimental results shown in Figs 7 and 8, it may be concluded that there is a possibility of a second generation of charge from the surface of the planar electrode when $E_p > 12$ MV/m. It is thought that the generated charges are electrons in this case, and the emission mechanism probably is same as that of the negative sharp electrode.

3.2 Positive breakdown mechanism

We propose a new mechanism concerning the onset of positive breakdown for DC voltage applications. With the assumption that electrons were emitted from the front of the planar electrode at voltages close to the breakdown in the positive needle case, the traveling locus of an anion created from a molecule by the attachment of an electron was calculated using an analysis of the EHD flow⁽¹⁹⁾⁽²⁰⁾. Fig. 10 shows an example of the anion locus and the streamlines of liquid flow. The anion can be carried away towards the needle electrode

Fig. 9. Field distributions at a voltage close to positive breakdown and at the negative critical voltage V_c for the two electrode geometries.

Fig. 10. An example of an anion traveling locus for a positive needle with $d=4$ mm, $r_n=10$ μm and $V=16$ kV.

because the flow velocity U was much larger than the ion drift velocity $U_\mu = \mu E$, where μ is the ion mobility and $\mu \approx 4 \times 10^{-9} \text{ m}^2/\text{V} \cdot \text{s}$ in transformer oil, as shown by the vectors. Although the anion locus slips a little out of the streamline of liquid flow due to the Coulomb force, the anion can reach the needle tip. Therefore, the space-charge effect on the field strength in front of the tip will be reduced due to the continuous invasion of anions; as a result, the field strength at the tip will be reinforced to a value slightly higher than the E_{ct} in Fig. 9. For example, under a voltage close to the breakdown $V = 16 \text{ kV}$ at $d = 4 \text{ mm}$ and $r_n = 10 \mu\text{m}$, CSM calculations indicated that when the space charge density in the vicinity of the tip was decreased as much as 10% by the invasion of anions, the increase of the field at the tip was about 4 MV/m. It is thought that a partial discharge at the tip initiated due to this slight field reinforcement may result in the initiation of rapid growth of a streamer. Provided that there is sufficient stress in the gap, the streamer will bridge the gap, causing a breakdown.

4. Conclusions

The characteristics of rapid current increase and breakdown voltage were measured in transformer oil subjected to a nonuniform DC field. The mechanism of positive breakdown was discussed on the basis of experimental and computed results. These are summarized as follows.

(1) The conduction current increases rapidly at voltages close to the critical value V_c . It was found from the dust figure method that a unipolar charge is injected by the sharp electrode. Violent liquid motion from the sharp electrode towards the planar one also occurs at voltages above V_c whatever the polarity of applied voltage. It is very likely that the rapid increase of the current at V_c is due to the injection of homocharges from the sharp electrode tip.

(2) The field strength in the gap is affected by the liquid motion because the distribution of space charge is dominated by its violent motion. At voltages close to the positive breakdown, the field strength E_p in front of a planar electrode with a space-charge effect is much higher than that in a

charge-free case. Both this local field enhancement on the planar surface and the dust figures suggest that there is a possibility of a new emission of electrons in the vicinity of a stainless steel planar surface at $E_p > 12 \text{ MV/m}$.

(3) It is suggested that the onset of positive breakdown may be caused by a reduction of the space-charge effect on the field strength at the sharp electrode tip due to the arrival of anions which are generated by the emission of electrons in front of the planar surface.

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