IET Generation, Transmission & Distribution

Research Article

Influence of hydrostatic pressure on creeping discharge characteristics over solid/liquid insulating interfaces under AC and DC voltages

ISSN 1751-8687
Received on 21st April 2017
Revised 21st June 2017
Accepted on 8th August 2017
E-First on 3rd January 2018
doi: 10.1049/iet-gtd.2017.0622
www.ietdl.org

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Abstract: This study deals with the influence of hydrostatic pressure on discharges propagating at solid/liquid insulating interface submitted to a divergent electric field under AC and DC voltages. The investigated insulator samples are of phenoplast resin (bakelite) and the considered liquid is mineral oil. The experimental results show that the hydrostatic pressure and the waveform, amplitude and polarity of voltage greatly influence the characteristic parameters of creepage discharges. The stopping (or final) length, L_f, which is the maximum extension of these discharges increases with voltage; it is reduced when applying a hydrostatic pressure. L_f increases quasi-linearly with the voltage and decreases quasi-linearly when the hydrostatic pressure is increased, whatever the voltage waveform. These results are of great interest especially for design and dimensioning of insulation systems in high voltage oil-filled apparatus and especially non-breathing components.

1 Introduction

The creeping discharges occurring at pressboard/oil interfaces result of the development of partial discharges initiated at the weakest sites of insulating systems used in oil-filled high voltage components of electrical power networks such as power transformers, bushings, power capacitors and so on; the weakest sites being generally the triple points. They are among the main electrical constraints; their evolution can indeed lead to erosion of pressboard and flashover, and thence in permanent damages requiring the repair of equipment or even their replacement. Thus the knowledge of optical and electrical parameters characterising these discharges and the understanding of the mechanisms and conditions implicated in their development are of great interest for industrial applications especially for the choice of constituents of insulating systems (insulator and oil) and the design of apparatus.

This type of discharges (creeping discharges) has been the subject of numerous studies [1–13]. It appears from the different results reported in the literature that the morphology of these discharges and the associated characteristics depend among others things on the thickness of solid insulator and the dielectric constant of both constituents (insulator and oil). So, it was reported that at atmospheric pressure, the stopping length of discharges increases quasi-linearly with the voltage and it decreases when the thickness increases, whatever the type of voltage wave form [5–10]. It has been also observed that hydrostatic pressure reduces the length of creeping discharges propagating over different types of insulator immersed in different kinds of oils as well as the associated currents and charges [10]. From the different experimental results reported in the literature, it appears that the electric field and capacitive effects play a fundamental role in the propagation mechanism of creepage discharges [5–10].

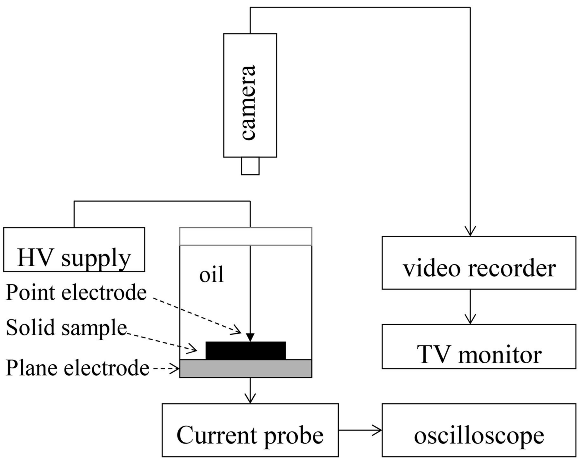
This paper is devoted to the influence of hydrostatic pressure on the characteristic parameters of discharges propagating at solid/liquid insulating interface when subjected to AC and DC in a point-to-plane electrodes system. Especially, the stopping length, L_f, of creepage discharges is investigated versus the applied voltage, U, and hydrostatic pressure, P. Relationships between these parameters (L_f, U and P) are also deduced. The tests are realised on solid insulating samples of phenoplast resin (bakelite) in the presence of mineral oil at hydrostatic pressure ranging 0.1–0.9 MPa. Bakelite is an interesting insulating material that is used in different high-voltage (HV) equipment such as bushing, dividers and capacitors.

2 Experimental arrangement

The experimental arrangement is similar to that one used elsewhere [5–10]; its schematic diagram is given in Fig. 1*a*. It includes a test cell, high voltage supplies, current probe, discharge recording and visualisation system. The HVs supplies are: (i) 50 kV–50 Hz transformer (Hipotronic type), connected to a control desk where a voltage regulator and a digital voltmeter are installed; these latter enable to raise the voltage at a rate of 2.0 ± 0.2 kV/s; and (ii) 200 kV–2 mA DC generator (Spellman type). For the continuity, we recall here the main features of this experimental set-up.

The test cell is cylindrical in shape with 90 mm high and 110 mm inner diameter. It contains the solid/oil insulation system and a point-to-plane electrode arrangement. It is constructed so that surface discharges develop radially as depicted in Fig. 1*b*. Its top cover is made of a transparent material, namely PMMA (Plexiglas) to allow visualisation of the discharges which develop on the insulator deposited on the lower cover constituting the flat electrode; this one is made of brass. The tip electrode with a radius of curvature of 1 μm is made of tungsten and is supported by the top cover. Its length is long enough so that it is in contact with insulator. The core of the test cell consists of two screwed parts: an upper part of 60 mm high made of Teflon and a bottom part issued from Plexiglas of 30 mm high enabling to control the contact between the point electrode and the solid insulator and to observe the discharge initiation.

The insulator samples are circular sheet of phenoplast resin (bakelite); the dielectric constant of which is of 4.8. Their diameter is 100 mm and their thickness 8 mm. The tested oil is mineral oil (naphthenic type) that is previously filtered and degassed; its dielectric constant is of 2.2. The Bakelite samples and oil were changed each time a flashover or tracking are observed on the solid surface. A system consisting of a piston and a pump enables to apply hydrostatic pressure up to 5 MPa.



a

b

Fig. 1 *Schematic diagram of the*
(a) Experimental setup and ***(b)*** Photograph of test cell

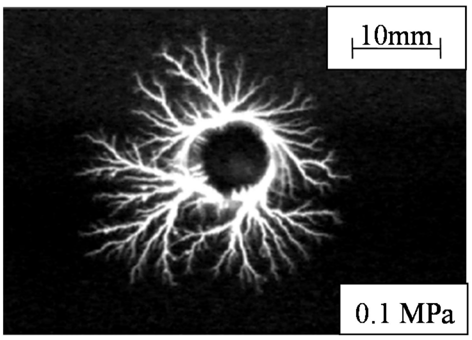


Fig. 2 *Example of creepage discharge propagating over bakelite surface immersed in mineral oil under negative DC voltage U− = 50 kV at 0.1 MPa*

The discharge current is measured using a current probe and a numerical oscilloscope (Tektronix DSA 601A). The current probe consists of a 50 Ω non-inductive resistor and two shielded high speed diodes connected back-to-back to protect the oscilloscope from over-voltages.

The development of the discharges is followed with a video camera (SONY SSC M370CCE (CCD Black and White Video Camera, High-Resolution 752 × 582, 0.3 Lux)) installed above the test cell, and a video recorder for immediate image storage connected to a TV monitor. This system enables to visualise the surface discharges through the light they emit (i.e. the optical observation of discharges is based on the integrated images). Due the too low time resolution of such a visualising system and its incapacity to measure the velocity of discharges, we focused our attention on the measurement of the maximum extension of discharges and more precisely to the maximum radius we called stopping length (or final length), L_f. L_f is measured as follows: the

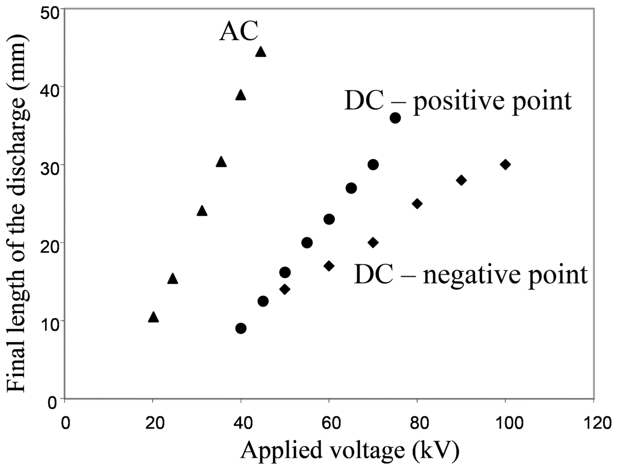


Fig. 3 *Evolution of the stopping length of discharges propagating over bakelite immersed in mineral versus the voltage for AC and DC at 0.1 MPa*

voltage is increased up to the desired value and maintained during 3 min. During this time, many discharges can be initiated. The value of L_f we took is the greatest one. This procedure is repeated a ten times for each value of the voltage; the time between two successive measurements is of 2 min. The value of L_f we plot on figures is the average value on these ten measurements. To distinguish the polarity of the discharge under AC, we recorded simultaneously the current.

3 Results and discussion

3.1 Influence of voltage

The creepage discharge appears when the applied voltage reaches a threshold value U_0. This initiation voltage U_0 depends on the voltage type and the polarity of the electrode point. We observed that U_0 is lower under AC voltage than under DC voltages. This is likely in relation with the injection and space charge phenomena and their effects on the electric field in the vicinity of the electrode point.

When the applied voltage is higher than U_0, different discharge patterns can be initiated. The characteristics of these discharges (shape, length, current, emitted light etc.) depend on the type of the voltage. Fig. 2 gives an example of typical discharge propagating at bakelite/mineral oil interface; note that the dark zone at the centre of the pictures corresponds to the shadow of the electrode point support.

For a given DC voltage, the stopping length, L_f, of positive creepage discharge is longer than that of the negative one as shown in Fig. 3. This is due to the space charges deposited over the solid surface which enhance the electric field components along the discharge channel leading to a longer streamer extension when the point is positive, and reduce the electric field resulting in a shorter streamer extension when the point is negative [5, 10]. L_f, measured under AC is longer than that measured under DC. Under AC, the hetero-charges accumulated at each-cycle and the fact that the reported values of L_f do not differentiate between positive and negative alternates of AC voltage make difficult the interpretation of the observed results.

The currents associated to creepage discharges exhibit different shapes. One can distinguish indeed either currents the shape of which are characterised by a continuous non-zero component on which are superimposed numerous short current pulses or currents constituted of pulses with a zero base; Fig. 4 depicts examples of such currents under DC. The first ones are generally observed when the point is positive and the second ones when the point is negative.

The current consisting of pulses with a zero base evidences a propagation by steps. Each step corresponds to a partial displacement of discharge after which the field drops practically to zero. When the field reaches a critical value, the discharge propagates again by a new step and so on. In that case, the

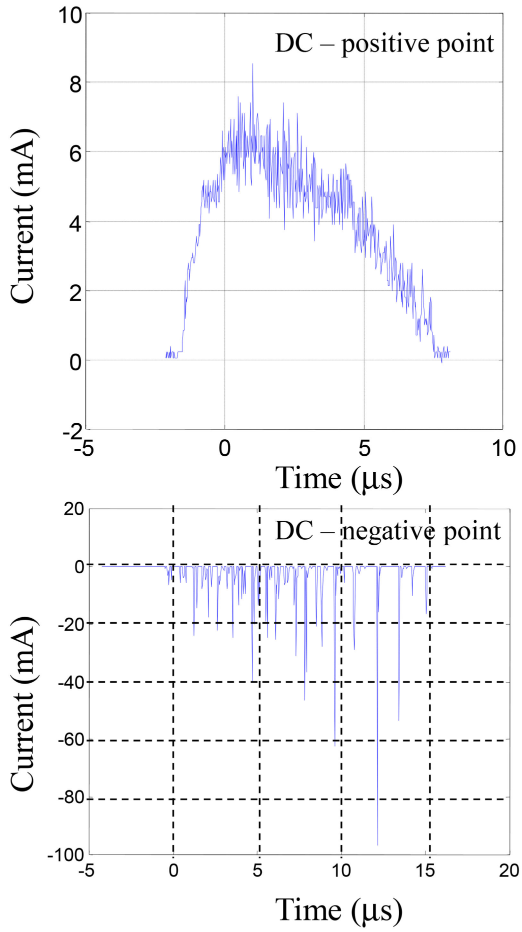


Fig. 4 *Current shape of positive and negative creepage discharges under DC voltage U = 50 kV*

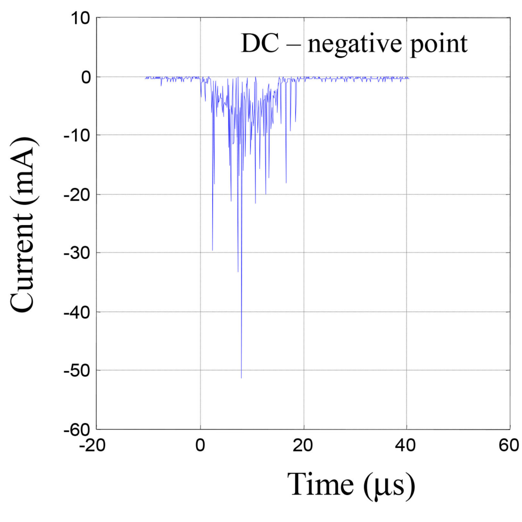


Fig. 5 *Current shape of negative creepage discharges under DC voltage U − = 75 kV*

discharges are slow compared to those the currents of which consist a continuous component. Similar results have been observed in liquids alone [14, 15].

When the point is negative, the higher the applied voltage, the more the probability of occurrence of current signals with a non-zero DC component similar to that observed when the tip is positive increases (Fig. 5). Note that single and very short current pulses with very high amplitudes reminding those observed in the liquid bulk, can be observed [14].

Under AC voltages, the currents observed for positive alternate are similar to those observed under positive DC voltage; and for negative alternate, they are similar to those observed under negative DC voltage.

3.2 Influence of hydrostatic pressure

The stopping length of creepage discharges, the duration, amplitude and number of corresponding current pulses and emitted light are greatly influenced by hydrostatic pressure. These characteristic parameters of discharges diminish when increasing the pressure. Fig. 6 shows how important the influence of the hydrostatic pressure on the density of discharge branches and their lengths. Moreover, Figs. 7–9 depict the evolution of L_f versus the voltage for different pressures and voltage waveforms. For a given pressure, one observes a quasi-linear increase of L_f with voltage. Such a linear variation has been reported by Hanaoka *et al.* [4] under impulse voltages at atmospheric pressure. On the other hand, for a given voltage, L_f decreases quasi-linearly when the pressure increases as shown in Figs. 10–12. Consequently, the number and amplitude of micro-discharges which contributes to the propagation of streamers decreased.

The fact that a moderate pressure reduces the volume and branches of discharges evidences the gaseous nature of creepage discharges. This reminds the observations reported on the streamers propagation in the liquids bulk (i.e. without the solid insulating) [15, 16]. Since the current presents many similarities with those accompanying the streamers in liquids, one can imagine a similar propagation mechanism of the creepage discharges [15]. Each elementary charge which corresponds to a current pulse contributes to the partial propagation. When a discharge occurs, there will be a light emission and the electrical field will drop to a level unable to maintain the discharge. The energy deposited will assist the streamer propagation by one step, i.e. a new partial elongation of branches. If the frequency and/or the amplitude of the current pulses are very high, the current tends to be roughly continuous and thence the discharge will be longer; the propagation tends to be continuous. Knowing the current shape or the corresponding electrical charge, one can compute the instantaneous velocity of creepage discharges using a similar approach as we used for the streamers propagating in liquids [15].

On the other hand, for a given voltage, the pressure required to suppress the positive discharges is more important than that required for the negative ones.

From the above results, one can describe the evolution of L_f versus the voltage U, for a given hydrostatic pressure P, by the following relationship [10, 17]:

$$L_f(U) = k_v(U - U_0) \quad (1)$$

where k_v is the slope of straight lines $L_f(U)$. U_0 is the initiation threshold voltage of discharge; it can be deduced by extrapolation of the straight lines at $L_f = 0$ mm. U_0 varies with the pressure. The higher the hydrostatic pressure, the higher U_0 is.

k_v is higher for AC voltage than for DC voltage; and under DC, k_v is higher with a positive point than with a negative one (i.e. for a given voltage and pressure, the discharge length is longer under AC than under DC voltages). Indeed, $k_v = 1.3 \pm 0.1$ mm/kV for AC; $k_v = 0.7 \pm 0.1$ mm/kV for positive DC and $k_v = 0.3 \pm 0.1$ mm/kV for negative DC. Note that the error on k_v is too great for DC – negative polarity. This is likely due to some dispersion in experimental measurements. The analyse of the results reported by Ohgaki and Tsunoda [18], gives $k_v = 1.2 \pm 0.1$ mm/kV for a paraffinic oil/acrylic sheet of 3 mm thickness interface, under a 0.5/2500 µs positive impulse voltage. Similarly for a given voltage, $L_f(P)$ can be described by the following relationship:

$$L_f(P) = k_p(P_{disp} - P) \quad (2)$$

where k_p is the absolute value of the slope of the straight lines $L_f(P)$. In our case, $k_p = 20 \pm 1$ mm/MPa for AC; $k_p = 32 \pm 1$ mm/MPa for positive DC and $k_p = 25 \pm 1$ mm/MPa for negative DC. P_{disp} is the hydrostatic pressure necessary for the disappearance of the discharge; it varies with the voltage and can

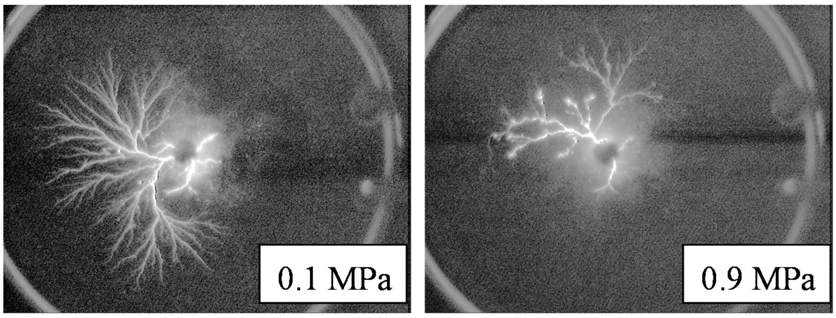


Fig. 6 *Influence of pressure on creepage discharges propagating at bakelite/mineral oil interface under AC voltage U_{rms} = 45 kV*

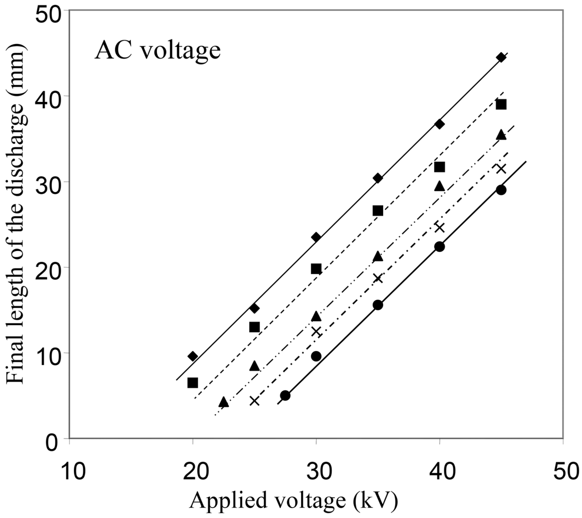


Fig. 7 *Stopping length of creeping discharges versus an AC voltage for different pressures: (black diamond) 0.1 MPa, (black square) 0.3 MPa, (black up-pointing triangle) 0.5 MPa, (diagonal cross) 0.7 MPa and (black circle) 0.9 MPa*

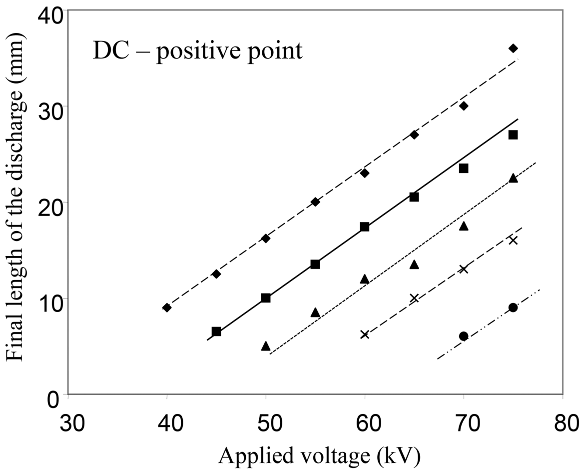


Fig. 8 *Stopping length of creeping discharges versus positive DC voltage for different pressures: (black diamond) 0.1 MPa, (black square) 0.3 MPa, (black up-pointing triangle) 0.5 MPa, (diagonal cross) 0.7 MPa and (black circle) 0.9 MPa*

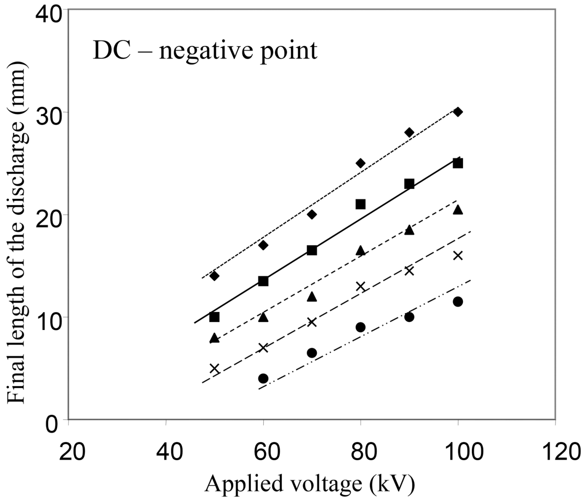


Fig. 9 *Stopping length of creeping discharges versus negative DC voltage for different pressures: (black diamond) 0.1 MPa, (black square) 0.3 MPa, (black up-pointing triangle) 0.5 MPa, (diagonal cross) 0.7 MPa and (black circle) 0.9 MPa*

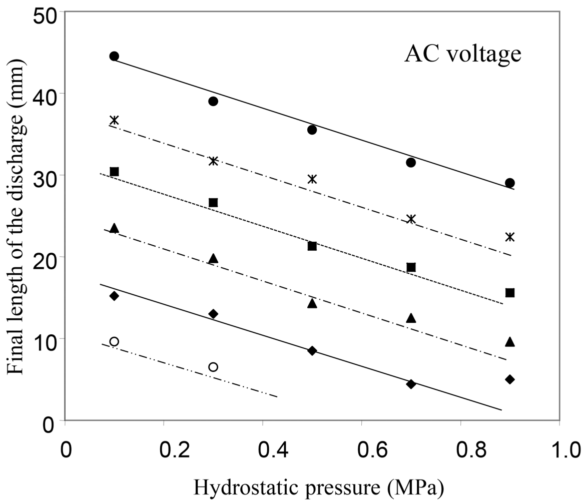


Fig. 10 *Stopping length of creeping discharges versus hydrostatic pressure for different values of AC voltage: (white circle) 20 kV, (black diamond) 25 kV, (black up-pointing triangle) 30 kV, (black square) 35 kV, (asterisk) 40 kV and (black circle) 45 kV*

be deduced by extrapolation from the straight lines at $L_f = 0$ mm. The higher the voltage, the higher P_{disp} is.

The above relationships between the stopping length, voltage and pressure can be very useful for design and dimensioning of insulation systems in high voltage oil-filled apparatus and especially non-breathing components.

4 Conclusion

In this work, we investigated the behaviour of creepage discharges propagating at solid/liquid interface when a hydrostatic pressure is applied to this insulating system. We showed that

- The characteristics of these discharges are greatly affected by the hydrostatic pressure. Indeed, the stopping length, the density of branches of discharges as well as the associated currents and emitted light signals are reduced when the pressure increases indicating that the physical nature of these discharges is gaseous. Such observations remind those reported in liquids.

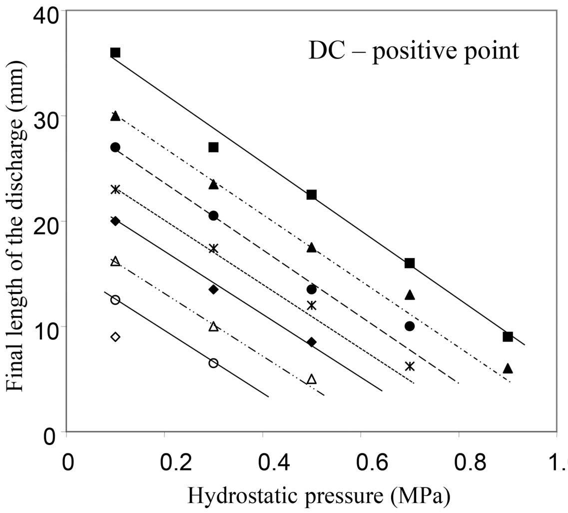


Fig. 11 *Stopping length of creeping discharges versus hydrostatic pressure for different values of positive DC voltage: (white diamond) 40 kV, (white circle) 45 kV, (white up-pointing triangle) 50 kV, (black diamond) 55 kV, (asterisk) 60 kV (black circle) 65 kV, (black up-pointing triangle) 70 kV and (black square) 75 kV*

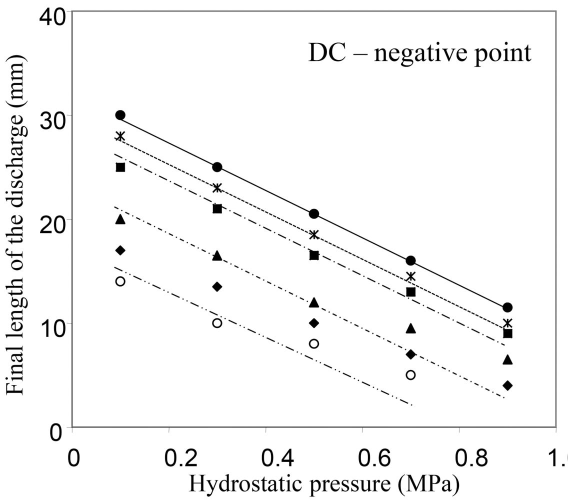


Fig. 12 *Stopping length of creeping discharges versus hydrostatic pressure for different values of negative DC voltage: (white circle) 50 kV, (black diamond) 60 kV, (black up-pointing triangle) 70 kV, (black square) 80 kV, (asterisk) 90 kV and (black circle) 100 kV*

- For a given pressure, the stopping length of discharges, L_f, increases almost linearly with the amplitude of voltage whatever the voltage waveforms (AC and DC).
- For a given voltage, L_f decreases almost linearly with pressure.
- At a given voltage, L_f under AC is longer than that initiated under DC.

The above results are very useful for design and dimensioning of insulation systems in high voltage oil-filled apparatus. And especially those concerning the influence of pressure are very helpful for the design of non-breathing components.

5 Acknowledgments

The authors extend their appreciation to the International Scientific Partnership Program (ISPP) at King Saud University for funding this research work through ISPP#0047.

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