STUDY ON AC CREEPAGE DISCHARGE PATTERNS AT THE INTERFACE OF NATURAL ESTER AND SOLID INSULATIONS

X. Yi and Z.D. Wang*
School of Electrical and Electronic Engineering, the University of Manchester, UK
*zhongdong.wang@manchester.ac.uk

Abstract: In this paper, the creepage discharge patterns on the surfaces of pressboard, Perspex and hard glass immersed in vegetable oil FR3 were studied. Partial discharges in divergent electric field under AC stress were monitored by means of commercial PD detector, wide-band resistor and high speed image recorder. The creepage discharge patterns on solid surface were compared to the discharges in open gap. From the higher apparent charge quantities, lower instantaneous voltage occurrence, larger current pulse amplitudes and durations, and longer streamers than in open gap, it can be concluded that the introduction of solid insulation would enhance the discharges. This enhancement exists in all the tests with solid surface present, irrespective of the type of the solid materials tested. It is found that the residual low density channels or bubbles left by previous discharge can be kept by the solid surface which in turn promotes the subsequent discharge. This could be the most plausible mechanism for the solid-liquid interface to impair the dielectric strength of the composite insulation system.

1 INTRODUCTION

In the oil-filled power transformers, solid insulations are customarily applied for the purposes of mechanical support, better cooling efficiency and dielectric integrity. However, the solid-liquid interface is usually considered as the electrical weak link which would compromise the dielectric strength of composite insulation system, because discharges might more easily propagate along the liquid-solid interface and lead to flashover and transformer failure [1-3].

Transformer industries are concerned about the failures caused by creepage discharges and spare no effort to minimize the failure risk due to creepage discharges in transformer insulation design, e.g. to arrange the solid barriers at right angles to the electric field to minimize the tangential electric stress, which is considered as the driving force of creepage discharge. The tangential electric stress in transformers should be designed below 1-2 kV/mm [4]. However, at struts and spacers, solid-liquid interfaces may still be parallel to the electric field, and become the cradles for creepage discharges and flashover. Therefore, it is necessary to understand how the presence of solid surface would change the discharge patterns and influence the overall dielectric performance of the composite insulation system.

Recently, natural esters are more and more popularly employed in distribution transformers due to good biodegradability and high resistance to fire risk. In this paper FR3 was used as the insulating liquid which is a type of natural ester refined from soya bean oil.

This paper reports creepage discharge patterns measured on the surfaces of pressboard, Perspex, and hard glass immersed in FR3 by means of commercial PD detector, wide-band resistor and high speed image recorder. The creepage discharge patterns on solid surfaces are compared to the discharges in open gap.

2 EXPERIMENT DESCRIPTION

2.1 Sample Processing

New pressboard samples were firstly dried in air circulating oven at 105 °C for 48 hours, and then dried in vacuum below 5 mbar at 85 °C for 24 hours. Impregnation was then carried out in vacuum below 5 mbar at 85 °C for 48 hours. The relative humidity of FR3 was controlled below 10% of saturation levels, and the moisture contents of impregnated pressboards were less than 0.5% by weight. The pressboard samples can be defined as dry according to [5]. Perspex and glass samples were immersed in FR3, and vacuum was applied to remove the surface moisture and ensure the thorough contact between the surfaces of solid samples and FR3 liquid.

2.2 Test Configuration

The experimental setup is shown in Figure 1. Needle to plate electrodes were adopted in order to initiate discharges. Medical needle was used as the point electrode, whose tip radius is 6-7 µm from the front view and 2-3 µm from the lateral view. The half taper shaped needle tip guarantees the close contact with solid surfaces. The plate electrode is 60 mm in diameter and with 5 mm edge radius. The gap distance is 50 mm long.

A 1 MΩ water resistor was connected between the test cell and the 240 V/70 kV supply transformer to limit the energy during breakdown/flashover and reduce the damage to the oil samples; besides, an over-current relay at the 240 V side was set to trip the power supply at 3 A current. Commercial LDIC-6 PD detector was connected in series with and under a 500 pF coupling capacitor to detect the PDs. In addition, a wideband 50 Ω resistor was used to obtain the discharge current signals which are sent to and displayed on an Agilent MSO8004A deep memory oscilloscope.

The optical refracting index of the streamer channel is different from the surrounding liquid [6], therefore the shape of streamer channel can be captured by shadowgraph cameras. In the test, Photron SA1 and MC1 high speed cameras were employed to observe the streamer channels in open gap and along the surface of solid insulations. Because pressboard is opaque, optical observations on creepage streamer by shadowgraph technique were carried out from the lateral side. For Perspex and glass samples, both high speed cameras were used to observe the streamer channels from both front and lateral views.

The oscilloscope and the high speed camera were triggered synchronously; therefore the current signals and the streamer images could be correlated for each discharge occurring under continuous AC stress. The deep memory of the oscilloscope facilitates recording the current details of discharges occurring in up to 26 consecutive AC cycles at a sampling rate of 125M points/s.

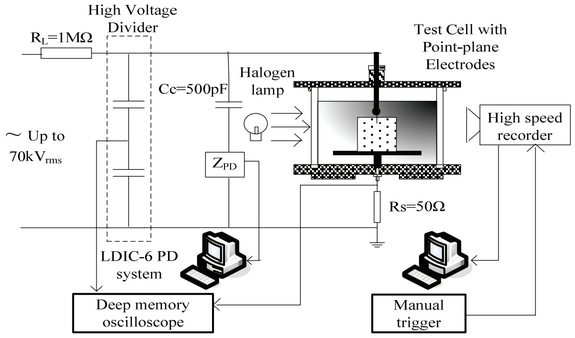


Figure 1: Diagram of experimental setup

3 CREEPAGE DISCHARGE PATTERNS ON SOLIDS

3.1 PDIV Results

The PD inception voltages in open gap and on the surfaces of solid insulations were measured by the PD detector. The AC supply was slowly ramped at an approximate rate of 0.5 kV/s. The voltage at which PDs exceeding 100 pC [7] start to appear is defined as PDIV. More than 15 PDIV tests were carried out for each case.

The PDIVs for tests on solid surfaces were about 18 kV, which are comparable with the PDIV in open gap. The presence of solid surface does not change the PDIV as compared with open gap, which is consistent with the observations in mineral oil as published in [4]. Besides, the PDIVs are similar on different solid materials. In [8] it is also reported that with this needle-plate electrode configuration, the discharge inception is also independent of liquid types. Therefore, it can be deduced that with needle to plate electrode, the discharge inception is determined by the needle tip, and PDIV values in extremely divergent field cannot be used to differentiate the material types of the insulating liquids and solids. Therefore it is necessary to study how the propagation of creepage discharges would be influenced by the solid materials at higher voltages.

3.2 Q-φ PD Patterns

When the pressboard and glass samples in FR3 were overstressed by high voltage (over 47 kV applied for 30 minutes on pressboard [8], and over 40 kV applied for 30 minutes on glass), treeing mark would appear on the surface of the solid insulations and the discharge pattern would change, therefore the voltage was applied up to 46 kV on pressboard and 39 kV on glass. For Perspex, there were neither visible changes on the surface nor the changes in PD pattern up to 46 kV at which flashovers occasionally occur.

The PD patterns in open gap and on the surfaces of solid insulations were measured. Figure 2 plots the discharges appearing in 60 seconds for both cases. It is indicated that after the solid surfaces were introduced, the apparent PDs are larger in amplitude than open gap, especially the discharges occurring in negative half cycles are greatly enhanced by the solid surface. Taken the test on Perspex for example, at 39 kV the maximum apparent PD in positive half cycle is as large as 3910 pC, which is almost three times that in open gap; while in negative half cycle, the maximum apparent PD on Perspex is 3450 pC, almost nine times that in open gap.

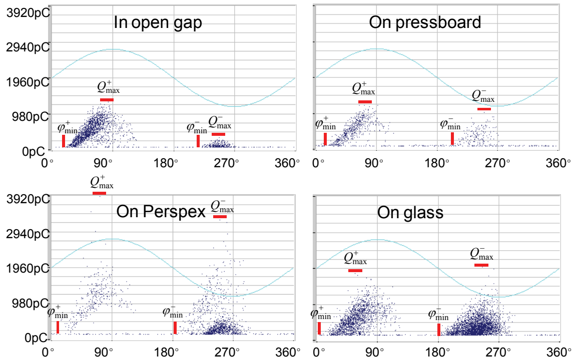
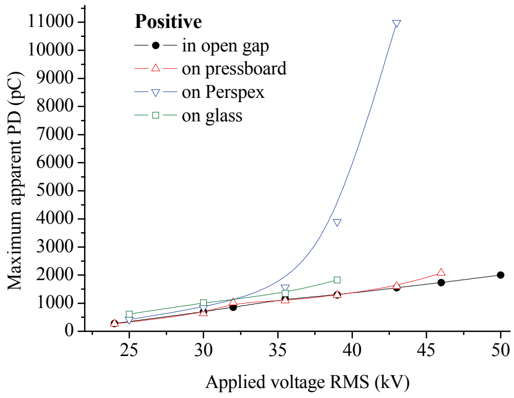
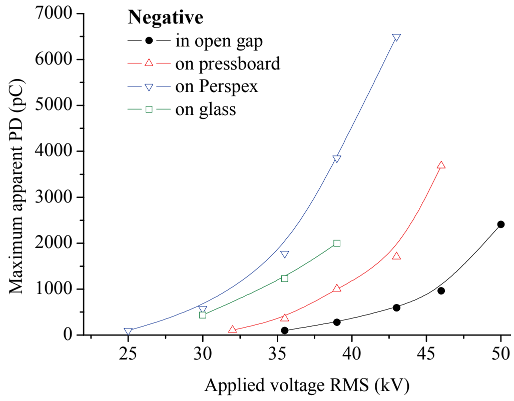


Figure 2: Q-φ PD patterns in open gap and on the surfaces of solid insulations in FR3 at 39kV

The information of maximum apparent PD value and the minimum PD occurrence phase angles were extracted from the recorded PD data to show the influence of the solid surfaces on discharges under various voltages. As shown in Figure 3, after the solid insulations were introduced, the maximum apparent PDs increase, especially in negative half cycles.



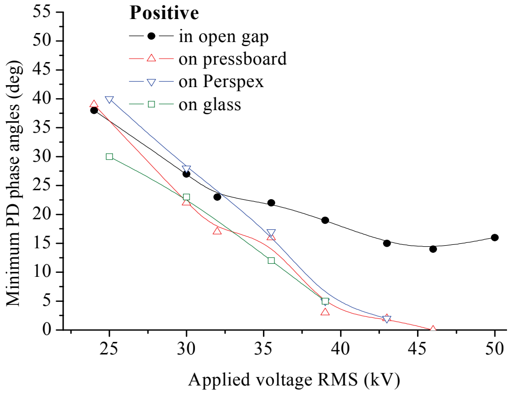
(a) in positive half cycle



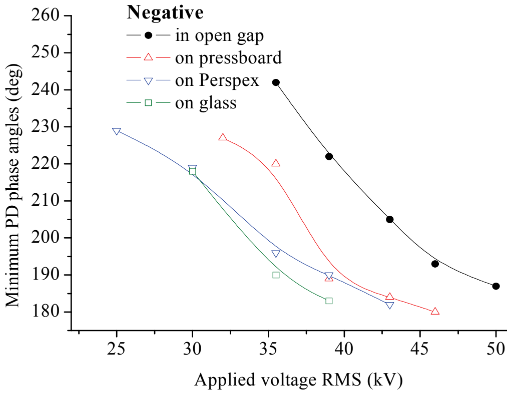
(b) in negative half cycle

Figure 3: Maximum apparent PD in open gap and on the surfaces of solid insulations

The minimum occurrence phase angles for readable PDs above system noise under different voltages are shown in Figure 4. At the same voltage, the PDs on solid surfaces can appear at smaller phase angles, namely at lower instantaneous voltages. For example, for open gap in FR3 at 39 kV, the smallest phase angle for PD occurrence is 19° in positive half cycle and 222° in negative half cycle while on the glass surface, the discharges can even occur at merely 5° in positive half cycle and 183° in negative half cycle. At higher voltages, the PD occurrence phase angles shift towards 0° or 180° more remarkably for the tests on solid surfaces.



(a) in positive half cycle



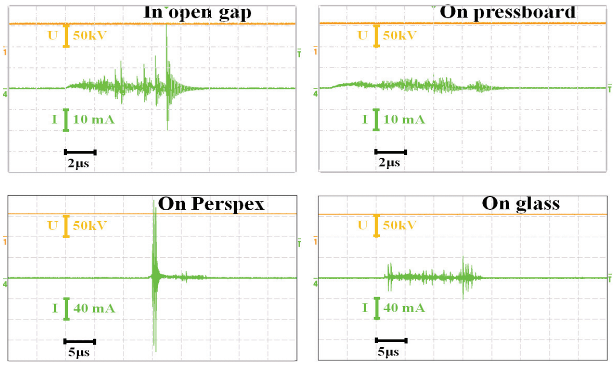
(b) in negative half cycle

Figure 4: Minimum PD phase angles in open gap and on the surfaces of solid insulations

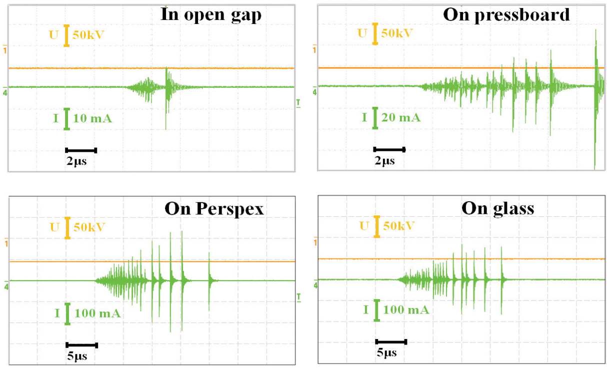
3.3 Discharge Current Characteristics

The promotion effect on discharges caused by the solid surfaces is further evidenced by the discharge current signals detected by the sampling resistor. Figure 5 shows the current signals in open gap and on the surfaces of solid insulations in FR3 at 39 kV.

For the discharge current signals in positive half cycles, there is always a continuous component superimposed by a train of discrete pulses. The introduction of solid surfaces would promote the discharges either by lengthening the sustaining time or by increasing the pulse peak as shown in Figure 5 (a).



(a) in positive half cycle



(b) in negative half cycle

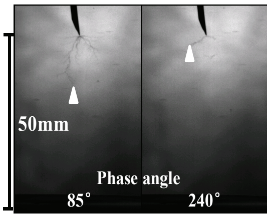
Figure 5: Discharge current signals in open gap and on solid surfaces in FR3 at 39 kV

In negative half cycles, the current signal contains a train of multiple discrete pulses, and with the growth of the discharge, pulses become larger with coarser intervals in between. In open gap at 39 kV, the negative discharge current lasts 3 μs with a pulse peak of 20 mA at the most, however on the Perspex surface, the discharge current signals could sustain for 20μs with a maximum pulse peak of 240 mA. From the much longer sustaining time, much more pulse number and larger pulse amplitude of the negative discharge current signals on the solid surfaces, it can be deduced that the presence of solid surfaces is evidently advantageous for negative discharges to develop.

3.4 Streamer length Information

High speed camera can capture the shape and length of streamer channels and help ascertain whether and how the discharge channels would be influenced by the presence of solid surfaces. . Figure 6 shows the longest streamer channels in open gap in FR3 at 43 kV and the longest streamer on the Perspex surface in positive and negative half cycles are shown in Figure 7 (c) and Figure 7 (a) respectively. The lengths of the longest streamer channels in open gap and on Perspex at 43 kV are summarized in Table 1.

The introduction of solid surfaces lengthens the streamer channels compared to open gap, especially the streamers in negative half cycle, which visually verifies the promotion effect of surface on discharges, particularly the negative discharges.



(a) positive (b) negative

Figure 6: The longest streamer in open gap for FR3 at 43kV (the triangle marks the tip of the longest streamer channel)

Table 1: Lengths of longest streamers in open gap and on Perspex at 43 kV

length of longest streamer (mm)	in open gap		on Perspex	
	positive	negative	positive	negative
	13	5	24	24

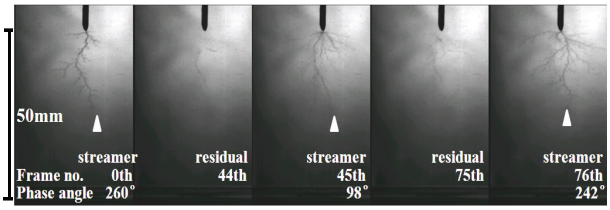
In summary, the patterns of apparent PD, current signals and streamer channels all indicate that, the introduction of solid surface tends to promote the creepage discharges especially those in the negative half cycles and enables more discharges to occur at smaller phase angles under AC stress. Irrespective of the types of solid materials tested, these phenomena generally exist.

4 INFLUENCE OF RESIDUAL LOW DENSITY CHANNELS ON CREEPAGE DISCHARGES

The pressure within streamer channels would drive the channels to expand and finally burst up [9-11]. Under AC stress, the consecutive discharges are not independent; instead, the discharges would leave some residual low density channels and promote the subsequent discharges. After the solid insulations are added, the surface works as a barrier for the expansion of streamer channels and some residual low-density channels or bubbles can be more easily kept by the solid surface during channel expansion.

From the videos of streamers on Perspex and glass, it is observed that the streamer channels of large discharges would remain on the solid surfaces for up to half an AC cycle, steering the direction and increasing the length of streamer channels of subsequent discharges of opposite polarity.

Figure 7 shows an example of the interactions among consecutive discharges of opposite polarities. As shown in (a), the first negative discharge occurred at a phase angle of 260°, and the longest channel was 24 mm long. After this discharge, its residual channels were preserved on the Perspex surface for 11 ms (shown in (b)) until next positive discharge occurred at 98° with the longest channel of 24 mm (shown in (c)). Comparing the two frames shown in (b) and (c), it can be found that some channels of the second positive discharge were in line with the remnant channels of the first negative discharge, which denotes the residual channels of discharges would direct the channels of the following discharge. Similarly, as shown in (d) and (e), the direction of channels of the third positive discharge were steered by the residual channels of the second discharge which were kept on the surface for 7.5 ms.



(a) (b) (c) (d) (e)

Figure 7: Streamer and residual channels of three consecutive discharges on the Perspex surface in FR3 at 43kV

(camera working at a speed of 4000 frames/second, the triangle marks the tip of the longest streamer channel)

Bubbles are advantageous for the development of discharges [12], therefore the discharge channels which follow the residual low density channels of the previous discharge can propagate more easily and longer than those in open gap, when comparing Figure 6 and Figure 7. The results presented in [13] also indicated that the negative streamer is more impacted by the solid surface. Therefore the length of negative streamer on Perspex can be almost as five times long as that in open gap as shown in Figure 6 (b) and Figure 7 (e). The influences of residual low density discharge channels on subsequent discharges can explain why the discharges, especially those in negative half cycles could be promoted by the solid surfaces.

5 CONCLUSION

With the help of commercial PD detector, wide-band resistor and high speed image recorder, the Q-φ PD pattern, current signals and streamer channels information were obtained for AC discharges in FR3 for open gap and on surfaces of pressboard, Perspex and glass. The results show that the surface of solid insulations would enhance the discharges in terms of higher apparent charge quantities, lower instantaneous voltage occurrences, larger current pulse amplitudes and durations, and longer streamers than in open gap. It is found that the residual low density channels or bubbles left by previous discharges can be easily kept by the solid surface which in turn promotes the subsequent discharge, which explains why the solid-liquid interface would impair the dielectric strength of the composite insulation system.

6 ACKNOWLEDGMENT

The authors would like to thank ALSTOM Grid, M&I Materials, National Grid, Scottish Power, TJ|H2b Analytical Services and UK Power networks for their financial and technical supports to the research consortium on ‘application of alternative insulating liquids for large power transformers’ at the University of Manchester. Special thanks are given to EPSRC Instrument Pool for the loan of high speed camera.

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