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Electrical Performance of Ester Insulating Liquids for Power Transformers

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SUMMARY

Ester insulating liquids, including both synthetic and natural esters, have been intensively studied in recent years, because the good biodegradability and high fire safety of these liquids bring the potential for manufacturers to produce and utilities to operate transformers which have lower intrinsic environmental risks. Depending on the application, transformers filled with ester liquids either directly reduce the environmental risk or allow reductions in the costs associated with the provision of additional environmental protection or leak mitigation. A collective research effort has been undertaken by the UK electric power industry on ester liquids to determine their suitability for use in higher voltage power transformers.

This paper focuses on the electrical performance of ester liquids. Experimental tests investigating discharge initiation, propagation and breakdown under both AC and lightning impulse voltages in non-uniform fields were carried out on a synthetic ester and a natural ester, using mineral oil as the benchmark for comparison. The results indicate similar discharge inception levels for all three types of liquid, however discharge propagation characteristics (discharge amplitude and number, streamer length and velocity) were found to be different and somewhat worse for esters compared with mineral oil. The tests also showed that ester liquids have relatively lower breakdown strengths than mineral oil. In addition, it was found that a pressboard surface does not influence streamer propagation and breakdown under lightning impulse voltage, but it does promote propagation and breakdown under AC voltage stress, particularly on discharges occurring in the negative half cycle.

These differences in the behaviour of ester liquids would probably need to be taken into account in the design of transformers at higher voltages.

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KEYWORDS

Power transformer, Natural ester, Synthetic ester, Mineral oil, Pressboard, Partial discharge, Streamer propagation, Breakdown, AC voltage, Impulse voltage.

1. INTRODUCTION

Ester liquids including both natural ester and synthetic ester are being considered as potential alternatives to mineral oil, due to their better environmental performance and for some liquids their higher fire point. Although these liquids have been widely used in distribution and traction transformers, it is still a significant step to adopt esters in high voltage power transformers because the very high cost and consequence of a factory test failure and the high level of safety and reliability required in service for these units, tends to lead to a cautious approach to any step change in technology. To mitigate these risks and open up the possibility of gaining the benefit from these materials, an ongoing research programme has been undertaken to gain as much understanding of the material characteristics as possible, including dielectric, thermal and chemical properties, material compatibility and ageing performance relative to the conventional mineral oil.

In the last decade an extensive effort has been made by several research groups to understand the properties of ester liquids, investigating breakdown voltage, moisture solubility, ageing, dissolved gas analysis, electrostatic charging tendency and cellulose material impregnation etc [1-6]. Most of the previous studies on electrical strength were carried out in uniform or quasi-uniform fields, and the results indicated that the breakdown strength of ester liquids is comparable to that of mineral oil under both AC and impulse voltages [3, 7-9]. However more recent studies have shown that ester liquids have a reduced performance in terms of streamer propagation and breakdown in divergent fields under impulse voltage [10, 11]. In the studies in divergent fields a needle electrode is normally used with the aim of initiating a streamer or partial discharge more easily. Although the stress at a needle electrode is unrealistic compared to the typical operating conditions in a transformer, it represents the situation where a defect or a source of discharge already exists, particularly in the course of long-term aging of a transformer in operation.

This paper focuses on the electrical performance of ester liquids in divergent fields including discharge initiation, propagation and breakdown under both AC and lightning impulse voltages. In addition, the influence of pressboard on discharge activity and breakdown performance in ester liquids is investigated and discussed. The study used a synthetic ester Midel 7131, a natural ester FR3 and for comparison, a mineral oil Gemini X.

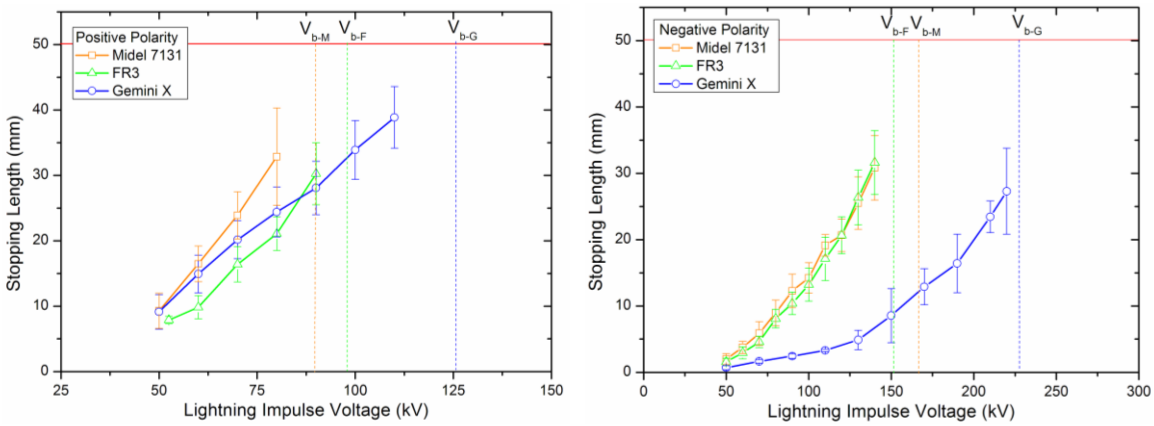
2. ESTER LIQUIDS UNDER LIGHTNING IMPULSE VOLTAGE

2.1. Experimental Conditions

The streamer characteristic and breakdown of ester liquids were studied using a standard 1.2/50 μs lightning impulse voltage and a needle-plane electrode system (with a variable gap distance set to 50mm for inception and propagation investigations) giving a strongly divergent electric field. The tip radius of the needle electrode was guaranteed to be 50±5 μm. A high-speed camera was used to observe inception and propagation of the streamer.

2.2. Streamer Inception

Inception voltages were determined by the appearance of a streamer captured by the high-speed camera. It should be noted that inception voltage is statistically distributed and the measured inception voltage is sensitive to the test conditions (sensitivity level of the camera, current measurement sensitivity and tip radius of needle electrode). Both shadowgraph and integral light images were used in this study. Around 10 measurements were carried out at each voltage level. As shown in Figure 1, the shortest positive streamer captured was about 5-10 mm long whereas the shortest negative streamer captured was 1 mm long. It was observed that the inception voltages of the esters are comparable to that of mineral oil at about 50kV for this test condition.



(a) Positive polarity (b) Negative polarity

Figure 1. Streamer length in ester liquids under both positive and negative impulse voltages, d=50 mm, $V_{b\text{-}M}$, $V_{b\text{-}F}$ and $V_{b\text{-}G}$ indicate the 50% breakdown voltages of Midel 7131, FR3 and Gemini X respectively.

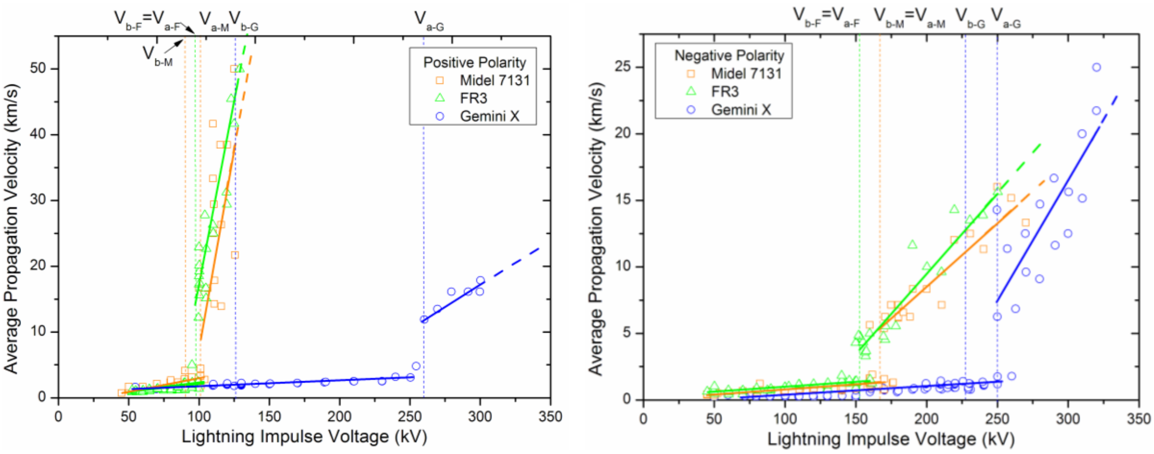
2.3. Streamer Propagation

In terms of streamer length as shown in Figure 1, esters behave similarly to mineral oil under positive polarity, i.e. the stopping length increases with applied voltage, in an approximately linear relationship before breakdown. Under negative polarity, a significant difference in streamer length characteristic exists between esters and mineral oil. In mineral oil the streamer length increases very slowly from inception voltage to about 140 kV, at which voltage the streamer looks like a round cloud with indistinguishable branches. Above 140 kV, the streamer length in mineral oil starts to increase rapidly. This phenomenon is also reported in [12] under step-like voltage stress. The negative streamer length of both esters increases almost linearly with applied voltage from inception, following the same characteristic as under positive polarity but at a lower rate.

Figure 2 shows average streamer velocity [13] against voltage for the three liquids. Before breakdown, average propagation velocity is calculated as the ratio of stopping length to propagating time, since streamers propagate typically at a constant velocity. Once breakdown occurs, average velocity is determined by gap distance divided by the time to breakdown.

Under positive polarity, the acceleration voltage of mineral oil (the voltage at which a significant increase in velocity is observed) is about 250kV, 2.6 times that of the ester liquids. Below the acceleration voltage the streamer velocity increases slowly with voltage. Once over acceleration voltage, streamer velocity in esters increases much more quickly with voltage than in mineral oil.

For negative polarity impulses, the acceleration voltage of mineral oil is similar to that for positive polarity at about 250kV, the acceleration voltage for ester liquids is again lower, but the margin is narrower with the acceleration voltage of mineral oil 1.6 times that of ester liquids. The velocity below the acceleration voltage is also lower for all the liquids than that under positive polarity. Above the acceleration voltage, streamer velocity increases with voltage in both ester liquids and mineral oil with a less marked difference between the rates, with mineral oil being marginally steeper.



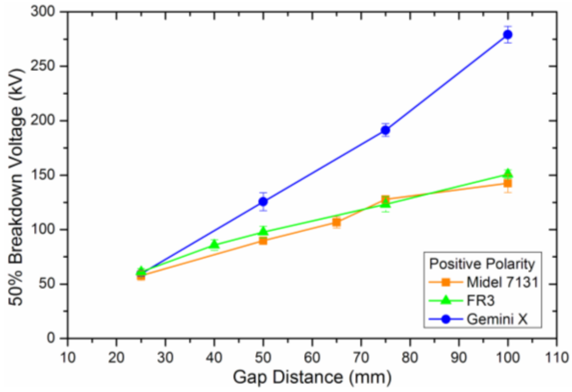
(a) Positive polarity (b) Negative polarity

Figure 2. Streamer velocity in ester liquids under both positive and negative impulse voltages, d=50 mm, $V_{a\text{-}M}$, $V_{a\text{-}F}$ and $V_{a\text{-}G}$ indicate the acceleration voltages of Midel 7131, FR3 and Gemini X respectively [13].

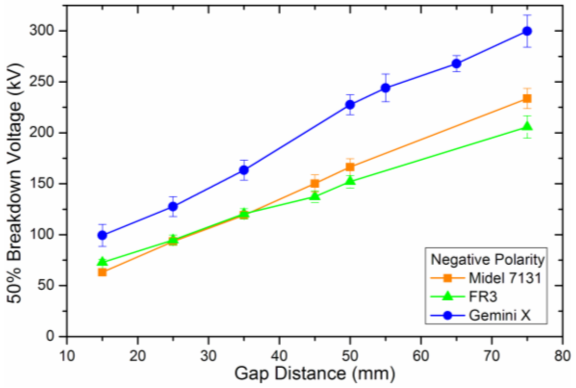
2.4. Breakdown Voltage Vs Gap Distance

Breakdown voltage at each gap setting was measured using the rising voltage procedure. The initial voltage applied was set at about 70% to 80% of the expected breakdown voltage. The voltage level was increased step by step (one shot per step) with an increment of 5 kV or 10 kV depending on the gap distance or expected breakdown voltage. 15 breakdowns per sample were obtained before changing both the electrode and liquid sample. An interval of at least 5 minutes was given between breakdowns to let the discharge by-products and gas bubbles diffuse.

As shown in Figure 3 [13], under positive polarity, breakdown voltages at a 25 mm gap are almost identical for esters and mineral oil. However with gap distances increased, both esters show lower breakdown voltages than mineral oil. Under negative polarity, breakdown voltages of esters are lower than that of mineral oil for all gaps observed, and the differences become bigger with gap distances increased. In addition, breakdown voltage under negative polarity is much higher than that under positive polarity for the same gap distance for all the liquids.



(a) Positive polarity



(b) Negative polarity

Figure 3. Breakdown voltages of ester liquids under both positive and negative impulse voltages [13].

3. ESTER LIQUIDS UNDER AC VOLTAGE

Partial discharge (PD) particularly in solid insulation has been found to be a precursor of failure so the minimization of PD is important both during factory tests and in service. PD can indicate material defects, such as protrusions or particle contamination from the manufacturing process or in-service ageing [14-16]. The insulating liquids in power transformers are therefore required to withstand high electrical AC stresses without inception of partial discharges.

With the development of the electro-optical technique, studies of partial discharge can incorporate discharge channel (streamer) detection using a high-speed camera [17]. In this section, the discharge characteristics and breakdown strength of ester liquids were studied in a needle-sphere divergent field under AC voltage. The tip radius of needle electrode is in the range of 1 to 3 μm and the diameter of the sphere electrode is 12.5 mm.

3.1. Discharge Initiation

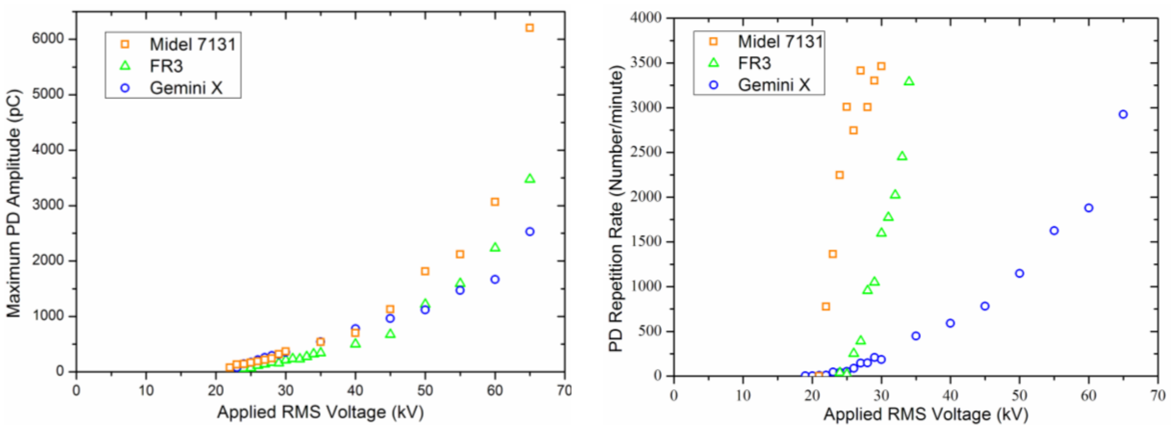
Discharge inception voltages were determined using both the traditional definition specified in IEC 61294 (with a 100 pC threshold) [18] and the optical capture of streamer initiation images, as shown in Table 1. A step increase in voltage with a 1 kV step and a 1 minute holding time at each step was used, instead of a continuous increase in voltage defined in IEC61294. The results show that the PD inception voltages of both ester liquids and mineral oil are quite similar. Discharge initiation is heavily dependent on the tip radius of the needle electrode, so inception voltage might not be a good method to evaluate the relative performance of ester liquids.

Table 1. Inception voltage of ester liquids and mineral oil, kV.

Inception Criterion	Midel 7131	FR3	Gemini X
IEC 61294	22.3	25.6	23.2
Streamer image	17.5	18.8	19.6

3.2. Discharge Propagation

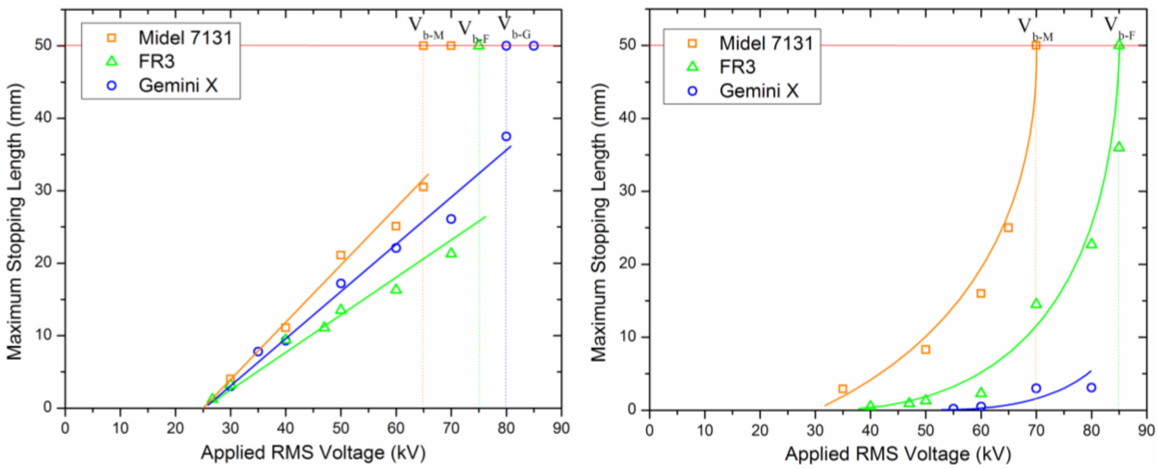
The discharge performance of ester liquids was also studied at overstressed voltages, i.e. higher than the inception voltage. Figure 4 shows the maximum PD amplitude and the PD repetition rate at applied voltages up to 65 kV [19]. The maximum PD amplitude indicates, to some extent, the propagation ability of partial discharges at a voltage level before breakdown occurs. From 25 kV to 45 kV, the maximum amplitudes of the partial discharges in all three liquids are similar, normally lower than 1000 pC. At higher voltages, the maximum PD amplitudes of ester liquids increase somewhat more quickly than those of mineral oil, with synthetic ester exhibiting the highest amplitudes. The PD repetition rate was found to be significantly higher in the ester liquids with a higher rate of increase with voltage than mineral oil.



(a) Maximum amplitude (b) Repetition rate

Figure 4. PD amplitude and repetition rate of ester liquids under ac voltage, d=50 mm [19].

The streamer characteristics of the liquids under AC voltage were obtained from inception to breakdown levels, as shown in Figure 5. ‘Maximum Stopping Length’ was used as the representative parameter, which is defined as the maximum length of streamers at a certain voltage level in the period of 100 AC cycles. The results show that the positive streamers (streamers observed in the positive half cycle of the AC voltage waveform) in ester liquids behave similarly to those in mineral oil. The maximum stopping lengths of streamers increase linearly with increasing applied voltage. However, the maximum stopping length of negative streamers, (streamers observed in the negative half cycle of the AC voltage waveform) depends on the type of liquid. The maximum stopping lengths of negative streamers increase significantly more rapidly with the increase of applied voltage in ester liquids than in mineral oil. It is striking that the features of streamer length characteristics under AC voltage are quite similar to those observed under lightning impulse voltage, showing that the lengths of negative streamers are more sensitive to the liquid nature than those of positive streamers.



(a) Positive half cycle (b) Negative half cycle

Figure 5. Streamer length of ester liquids under both positive and negative half cycles of ac voltage, d=50mm, $V_{b\text{-}M}$, $V_{b\text{-}F}$ and $V_{b\text{-}G}$ indicate the 50% breakdown voltages of Midel 7131, FR3 and Gemini X respectively.

3.3. Breakdown Voltage Vs Gap Distance

Breakdown voltage tests were carried out in both ester liquids and mineral oil at gap distances from 2 mm to 100 mm under AC voltage, as shown in Figure 6. Breakdown voltages of ester liquids are generally marginally lower than those of mineral oil, except for the smallest gap distance used. In addition, it was noticed that breakdowns in mineral oil are only induced by positive streamers, while breakdowns in esters can be induced by both positive and negative streamers. This agrees with the conclusion in the previous section that negative streamers are difficult to propagate in mineral oil. It might also be part of the reason why the breakdown voltages of esters are relatively lower than those of mineral oil, since there could be a higher probability in a given time of a streamer leading to breakdown in esters (induced during positive and negative half cycles) than in mineral oil (induced only in the positive half cycles).

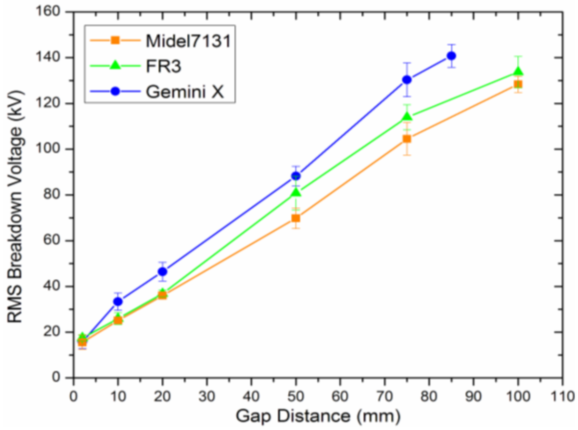


Figure 6. Breakdown voltage of ester liquids under ac voltage.

4. INFLUENCES OF PRESSBOARD

In oil-filled transformers, pressboard is customarily used to partition large oil gaps, for mechanical support, to direct liquid flow for better cooling efficiency and to ensure dielectric strength. However, the solid-liquid interface is usually considered as an electrical weak link, because discharges might more easily propagate along the liquid-solid interface and lead to flashover. In scrapped transformers, carbonized tracks or 'treeing' marks left by creepage discharges on pressboard barriers are sometimes observed [20-22].

To minimize the probability of creepage discharges, the layout direction of the pressboard barriers is arranged to follow the equi-potential lines so that the tangential stress along the pressboard surface is controlled below 1-2 kV/mm [23]. However, at certain positions such as the edge of winding spacers, pressboard-oil interfaces may still exist parallel to the electric field, and become the sites for creepage discharges and flashover. Therefore, it is necessary to understand how the presence of a pressboard surface would change the discharge patterns and influence the overall dielectric performance of the composite insulation system. In this section, the influences of a pressboard surface parallel to the electric field were investigated under both lightning impulse voltage and AC voltage stress.

4.1. Lightning Impulse

Figure 7 shows the stopping length of streamers on a synthetic ester/pressboard interface under both positive and negative polarities at a 50 mm gap (the dashed line shows the results in an open liquid gap). Streamer length under both polarities increases gradually with the increase of applied voltage. It is clearly observed that no promotion effect was introduced by the pressboard under either polarity. Similar trends were observed on natural ester/pressboard interface. There is only a minor increase of stopping length at high

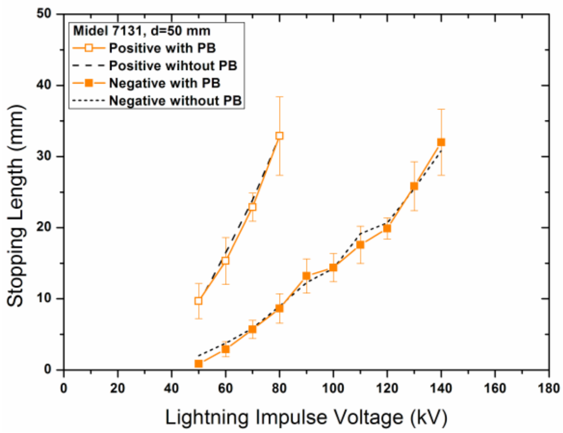
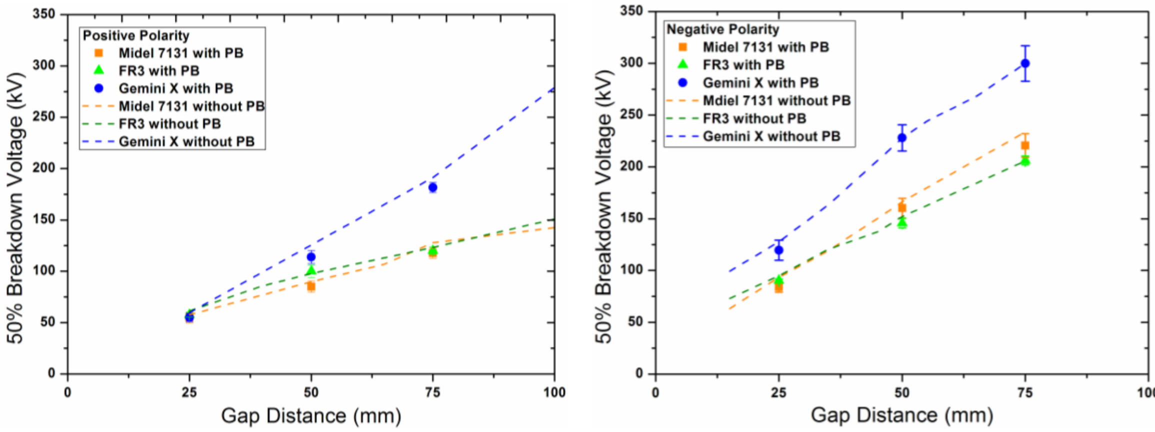


Figure 7. Influence of pressboard on streamer length under both positive and negative lightning impulse voltage, d=50 mm, Midel 7131.

voltage levels with the presence of pressboard in natural ester. Furthermore, the breakdown voltages on esters/pressboard interface were found to be similar to those in open ester liquids gaps under both positive and negative polarities, as shown in Figure 8. A similar phenomenon was also reported at a gap distance of 100 mm under both polarities [11].



(a) Positive polarity (b) Negative polarity

Figure 8. Breakdown voltages on esters/pressboard interface under lightning impulse voltages.

Below the acceleration voltage, the streamer velocity increases slowly as the voltage level is increased, generally in the range of 1.0 km/s to 3.0 km/s for both cases of with and without pressboard interface in the three liquids. Once the transition into fast mode is made, it was found that the introduction of pressboard does not influence the streamer velocity in ester liquids, but significantly promotes the streamer velocity in mineral oil at positive overstressed voltages leading to a large reduction of acceleration voltage, about 60 kV for the gap distance of 50 mm.

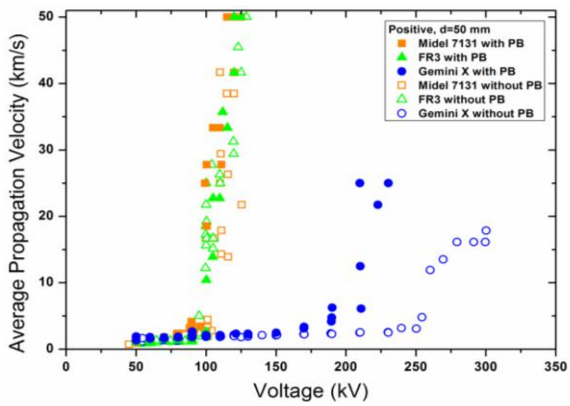


Figure 9. Influence of pressboard on streamer velocity under positive lightning impulse voltage, d=50 mm.

4.2. AC Voltage

The introduction of pressboard appears to have no influence on the Partial discharge initiation voltage (PDIV) in both ester liquids and mineral oil, because the PDIVs in an open gap are comparable with those on pressboard surface.

PD patterns at higher voltage levels, taking during the tests in synthetic ester as an example, are shown in Figure 10, plotting the discharges occurring in a 60 second period. With the pressboard present, the negative PDs are obviously enhanced compared to open gap. At 35.5 kV, PDs in both half cycles are greater in number and larger in amplitude than in the open gap; the maximum amplitude of PDs in the negative half cycles is higher than that of

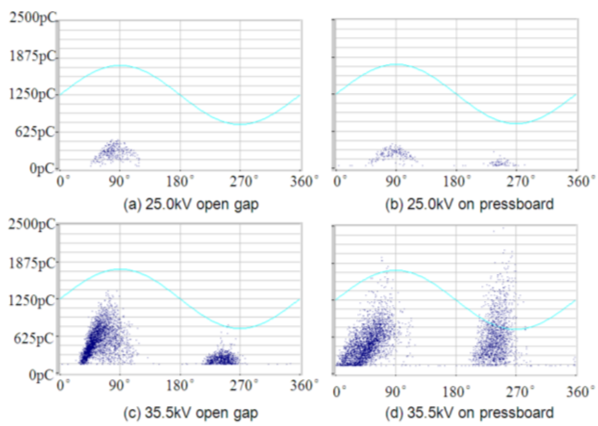


Figure 10. Q-φ PD patterns in open gap and on pressboard in MIDEL 7131.

the PDs in the positive half cycles. In addition, compared with the open gap test many discharges occur at smaller phase angles, even close to 0° or 180°. Similar developing stages of discharges in open gap and on pressboard also exist in natural ester and mineral oil.

A high speed camera was used to capture the shape and length of the streamer channels and to help identify the influence, if any, of the solid surface. For example, Figure 11 shows the streamer channels in an open gap and on a pressboard surface in natural ester at 46.0 kV. The longest positive streamer was 26 mm in open gap and 38 mm on pressboard; the streamers are lengthened more significantly by the pressboard surface in the negative half cycle where the longest negative creepage streamer was 28 mm, whereas its counterpart in the open gap was 6 mm long.

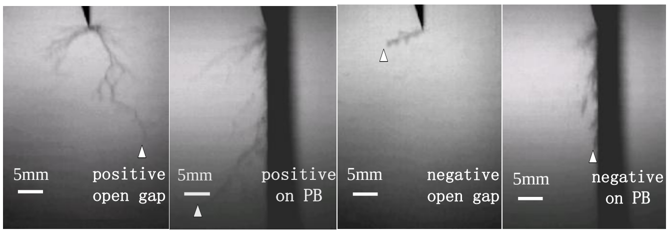


Figure 11. Images in open gap and on pressboard in FR3 at 46 kV (the triangle marks the tip of the longest streamer channel).

5. CONCLUSION

Experimental studies on the electrical performance of two ester liquids and a mineral oil used as benchmark, with and without a pressboard interface, from discharge initiation to propagation and, ultimately, breakdown were carried out in non-uniform fields under both lightning impulse and AC voltages.

At the discharge initiation stage, the results under both lightning impulse and AC voltages show that the ester liquids have similar inception levels to mineral oil and the presence of pressboard has no influence on the inception voltages.

Under lightning impulse voltage, streamers in ester liquids propagate further and faster than those in mineral oil at the same voltage level, ester liquids have much lower acceleration voltage indicating a lower tolerance to fast events than mineral oil. The presence of pressboard does not influence the streamer length and velocity in ester liquids, but there is a reduction in the positive acceleration voltage in mineral oil. Under AC voltage, a similar pattern was observed on streamer lengths. Esters show discharges in both half cycles at lower AC voltages whereas the discharges detectable by a commercial PD detector are only in positive half cycles for mineral oil. With the presence of pressboard, creepage discharges occurring in the negative half cycle in esters are enhanced. PD measurements at overstressed voltages, (higher than inception voltage), show that the PD repetition rate (number per minute) for ester liquids increases much more quickly with voltage than it does in mineral oil.

At the breakdown stage, ester liquids generally have lower breakdown voltages than mineral oil under both lightning impulse and AC voltages. The difference in breakdown voltage between ester liquids and mineral oil is increased at larger gap distances. To compensate for this volume effect, additional pressboard barriers may need to be added as partitions in large oil gaps in an ester filled transformer.

Overall this work implies that although discharge inception is similar in all the liquids, propagation is generally faster and at lower voltages in ester liquids when compared with mineral oil so ‘discharge free design’ becomes more than ever, significant for ester filled power transformers.

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