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Ester Insulating Liquids for Power Transformers

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SUMMARY

The properties of ester insulating liquids, including both synthetic and natural esters, offer the potential for transformers with lower fire risk and greater environmental compatibility when compared with those filled with mineral oil. This potential has led to intensive studies of the electrical and thermal performance of ester liquids in recent years.

A collective research effort was made to study ester liquids by a number of companies within the UK electric power industry particularly in respect of their application to large power transformers. With a liquid provider and a transformer manufacturer, extensive research has been carried out at a university into the dielectric aspects of the insulating liquids to prove the feasibility of using an ester liquid in place of mineral oil in large high voltage power transformers.

This paper sets out the results of this research focusing mainly on the electrical performance of ester liquids. Experimental tests in both quasi-uniform and non-uniform electric fields including discharge initiation, propagation and breakdown were carried out under both AC and lightning impulse voltages. In addition to open oil gaps, the influence of pressboard in parallel to the oil gap was also investigated. The comparison between the performance of ester liquids and mineral oil, allows conclusions to be made regarding the application of ester liquids in power transformers.

KEYWORDS

Power transformer, natural ester, synthetic ester, mineral oil, pressboard, breakdown, partial discharge, streamer, AC voltage, lightning impulse voltage.

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1. INTRODUCTION

Ester liquids, including both natural and synthetic esters, have been considered as potential alternatives to mineral oil, owing 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 ester liquids in high voltage power transformers. 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, tend 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, a research programme has been undertaken to gain as much understanding of the material characteristics as possible, including dielectric, thermal physical and chemical properties, material compatibility and ageing performance relative to 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, streaming electrification and cellulose material impregnation etc [1-7]. The majority of insulation materials inside a transformer, i.e. between turns, disks and windings, are experiencing a quasi-uniform electric field. Research in quasi-uniform electric fields indicated that the breakdown strength of ester liquids is comparable to that of mineral oil under both AC and lighting impulse voltages [3, 8-10]. On the other hand, non-uniform electric fields, which exist at the end of a winding, or which might be caused by manufacturing defects e.g. a protrusion on the copper conductor or contamination resulting from long term, in-service degradation e.g. particle and moisture in the oil, need to be considered in detail when a change of dielectric properties of the insulation is made. Recent studies have shown that ester liquids have a reduced performance for pre-breakdown and breakdown in non-uniform electric fields under impulse voltage [11-13].

This paper focuses on the electrical performance of ester liquids in both quasi-uniform and non-uniform electric 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, Gemini X was taken to be a representative mineral oil.

2. ELECTRICAL PERFORMANCE UNDER AC VOLTAGE

2.1. In quasi-uniform electric field

The AC breakdown voltage test in a quasi-uniform electric field such as defined in IEC 60156 is commonly used as one of the quality check and acceptance tests for insulating liquids before filling new transformers or during routine maintenance. Although it has been reported that AC breakdown voltages of new clean ester liquids are similar to that of mineral oil, due consideration must be given to the question if these liquids have different electrical performances or not when they are contaminated during transformer operation.

The AC breakdown voltages of ester liquids were studied using an automatic tester, DPA75, offering a quasi-uniform electric field between the pair of VDE electrodes of a 1 mm gap distance. The breakdown tests followed the procedure described in ASTM D 1816, with the time interval between two successive breakdowns increased from 1 minute (generally for mineral oil) to 5 minutes (particularly for ester liquids).

Table 1 shows the average breakdown voltage (BDV) and standard deviation (SD) of ester liquids and mineral oil. The liquid samples were filtered, dehydrated and degassed as described in [8]. For processed samples, ester liquids have a similar breakdown voltage to that of mineral oil.

Table 1. AC breakdown voltage of ester liquids obtained at a 1 mm VDE electrode gap.

Liquid	Midel 7131	FR3	Gemini X
BDV, kV	45.1	44.5	47.7
SD, kV	4.3	4.6	4.1

However when the liquids are contaminated with particles, obvious differences were noticed between their breakdown voltages. Figure 1 shows the BDV and SD of ester liquids and mineral oil with cellulose particle contamination. The results show that the breakdown voltages of both ester liquids and mineral oil decrease with the increase of cellulose particle content, which conforms to the previous research in [14]. However, the breakdown voltage of mineral oil seems to be more sensitive to the particle contamination than ester liquids. The possible reason is that the particle motion is restrained in more viscous liquids e.g. ester liquids than in less viscous liquids e.g. mineral oil [15].

As the water content in the oil is increased, there is a similar trend between ester liquids and mineral oil if relative humidity (RH) is used as the criterion. Figure 2 plots the BDV and SD of ester liquids and mineral oil with increasing relative humidity. The breakdown voltages of the clean samples are not affected by moisture level up to 20% RH. Once above 20% RH, their breakdown voltages are gradually reduced with the increase of relative humidity.

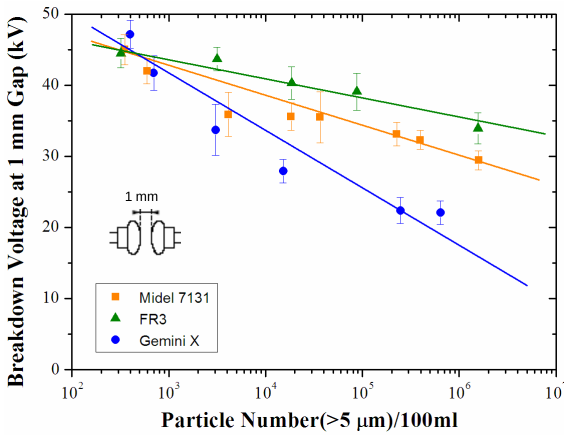


Figure 1. AC breakdown voltage of ester liquids with cellulose contamination in a quasi-uniform field.

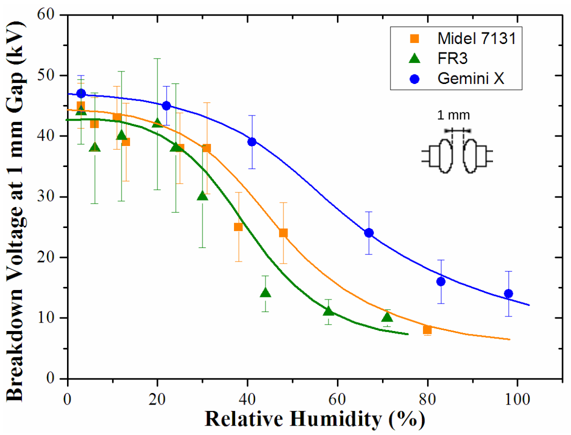


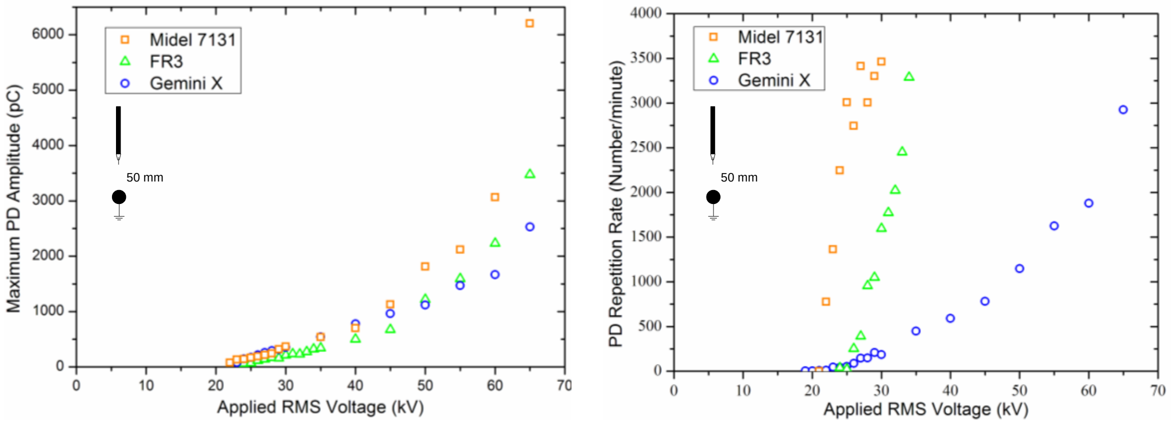
Figure 2. AC breakdown voltage of ester liquids with water contamination in a quasi-uniform field.

2.2. In non-uniform electric field

An electro-optical technique was used to study partial discharges incorporating discharge channel (streamer) detection using a high-speed camera [16]. In this section, the discharge characteristics and breakdown strength of ester liquids were studied in a non-uniform needle-sphere electric field under AC voltage. The tip radius of the needle electrode was in the range of 1 to 3 μm and the diameter of the sphere electrode was 12.5 mm.

Figure 3 shows the maximum PD amplitude and the PD repetition rate at applied voltages up to 65 kV [17]. The maximum PD amplitude indicates, to some extent, the propagation ability of partial discharge at a voltage level before the occurrence of breakdown. 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

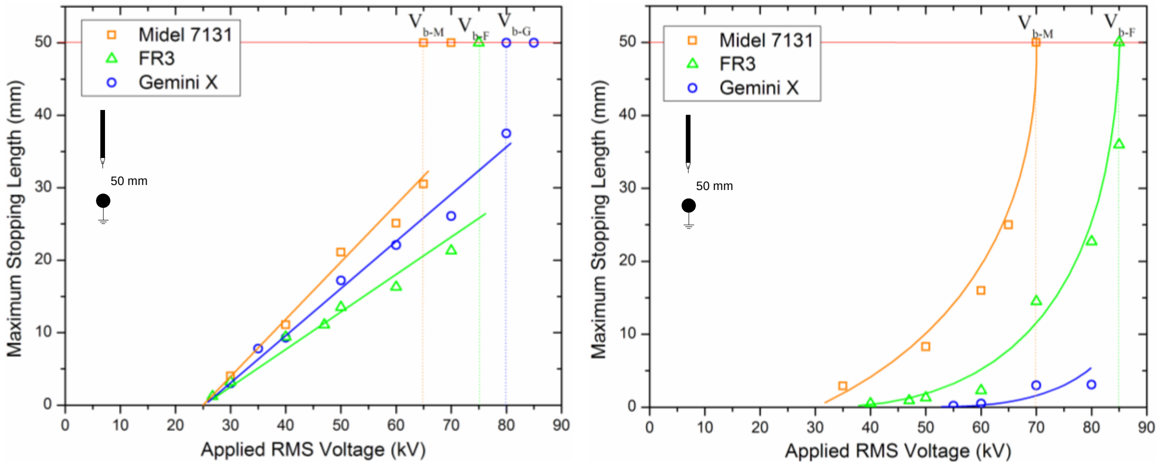
PD repetition rate was found to be significantly higher in the ester liquids than in the mineral oil, with a higher rate of increase if voltage is further increased.



(a) Maximum amplitude (b) Repetition rate

Figure 3. PD amplitude and repetition rate of ester liquids under AC voltage, d=50 mm [17].

The streamer characteristics of the liquids under AC voltage were obtained from inception to breakdown levels, as shown in Figure 4. 'Maximum Stopping Length' was used as the representative parameter, which is defined as the maximum length of streamer 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 AC voltage) in ester liquids behave similarly to those in mineral oil. The maximum stopping lengths of streamers increase linearly with increasing applied voltages. However, the maximum stopping lengths of negative streamers, (streamers observed in the negative half cycle of AC voltage) depend 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.



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

Figure 4. Streamer length of ester liquids under both positive and negative half cycles of AC voltage, d=50mm, V_{b-M}, V_{b-F} and V_{b-G} indicate the 50% breakdown voltages of Midel 7131, FR3 and Gemini X respectively.

AC breakdown voltage was tested using a rising-voltage procedure (2 kV/s) in both ester liquids and mineral oil at gap distances from 2 mm to 100 mm, as shown in Figure 5. Breakdown voltages of ester liquids are 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 ester liquids are induced by both positive and negative streamers. This is in agreement with the previous observation that negative streamers are difficult to propagate in mineral oil. It might also be part of the reason why the breakdown voltages of ester liquids are relatively lower than those of mineral oil.

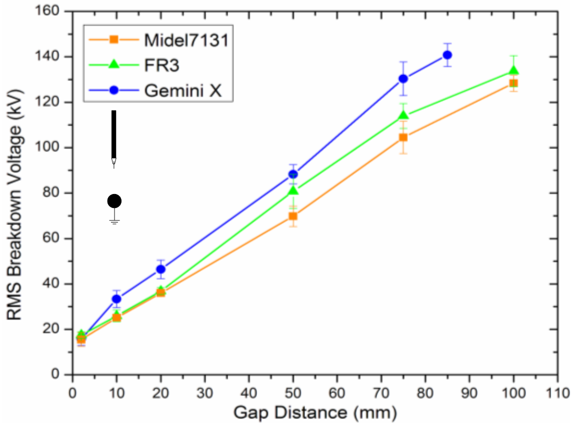


Figure 5. AC breakdown voltage of ester liquids in a non-uniform field.

2.3. Influence of parallel pressboard

In oil-filled transformers, pressboard barriers and components are customarily used to partition large oil gaps to increase dielectric integrity, to provide mechanical support and to direct liquid flow for better cooling efficiency. However, the solid-liquid interface is usually considered as the 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 [18-22]. To minimize the probability of creepage discharges, the insulation structure is usually designed to minimize the tangential electric field along pressboard surface since this field is the driving force of creepage discharges. Whenever possible, the direction of the pressboard barrier is arranged to conform with the electric equi-potential line and thus the tangential stress along pressboard is controlled below 1-2 kV/mm [23]. However, at struts and spacers, pressboard-oil interfaces may still exist parallel to the electric field, and become weak points for the initiation of creepage discharges. Therefore, it is necessary to understand how the presence of a pressboard surface changes the discharge patterns and influences the overall dielectric performance of the composite insulation system.

The partial discharge inception voltage (PDIV) for an open gap and on a pressboard (with moisture less than 0.5% by weight) surface in ester liquids and mineral oil are listed in Table 2. These results indicate that the presence of a pressboard surface does not change the PDIV as compared with an open gap, which is consistent with the previous observations in [23]. In addition, the PDIV is also independent of the liquid type, which is in line with the observation that in uniform electric fields, the breakdown voltages of ester liquids along pressboard are comparable with that of mineral oil [24], because it is generally considered that breakdowns in uniform electric fields are mainly determined by the discharge inception [25].

Table 2. PDIVs for open gap and on pressboard surface in ester liquids.

PDIV (kV)	Midel 7131		FR3		Gemini X	
	Mean	SD	Mean	SD	Mean	SD
Open gap	17.5	0.5	18.3	0.3	17.9	1.2
With PB	18.3	0.7	17.6	0.4	16.8	0.6

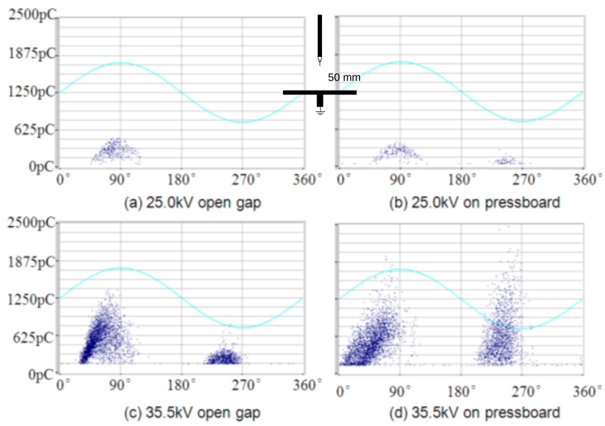


Figure 6. Q-Φ PD patterns in open gap and on pressboard in synthetic ester Midel 7131.

PD patterns at higher voltage levels, taking the tests in synthetic ester as an example, are shown in Figure 6, plotting the discharges occurring in 60 seconds. With the pressboard present, the negative PDs are obviously enhanced compared to the open gap; At 35.5 kV, PDs in both half cycles are greater in number and larger in amplitude than in the open gap and the maximum amplitude of PDs in the negative half cycles is higher than that of the PDs in the positive half cycles. Compared with the open gap test, many discharges occur at smaller phase angles, even close to 0° or 180°.

The current signals in both positive and negative half cycles, taking the natural ester as an example, are shown in Figure 7. The promotion effect on discharges caused by pressboard surface is further verified by the longer sustaining time and larger pulse amplitude of current signals, especially for discharges at the negative half cycles.

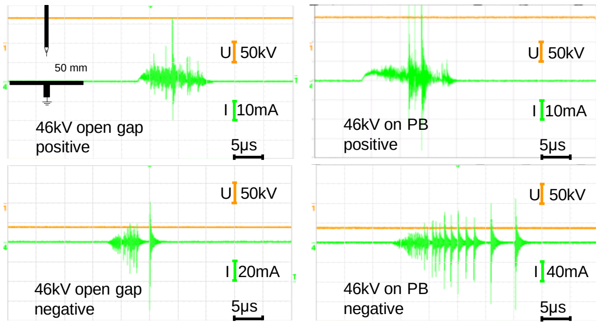


Figure 7. Current signals of discharges in natural ester FR3 at 46.0 kV.

To sum up, the introduction of pressboard tends to promote discharges especially those in the negative half cycles and enables more discharges to occur at smaller phase angles, even around 0° or 180° in all three liquids tested under AC stress. The most likely explanation for the promotion effect of pressboard on discharges is the presence of hetero-charges [26-29] and residual bubbles left by the previous discharges [30]. Because of higher discharge intensity and higher viscosity, this discharge promotion effect is much more evident in ester liquids than in mineral oil, especially when the samples are stressed at higher voltages. The enhancement of negative discharges by pressboard surface could increase the probability of flashover failure triggered by large negative discharges in ester liquids.

3. ELECTRICAL PERFORMANCE UNDER IMPULSE VOLTAGE

3.1. In quasi-uniform electric field

The breakdown voltage of ester liquids and mineral oil in a 3.8 mm sphere-sphere gap was investigated using negative 1.2/50 μs lightning impulses. The liquid samples were filtered, dehydrated and degassed before testing. Various testing methods including rising-voltage, up-and-down and multiple-level methods were used. As shown in Figure 8, the results indicate that the testing methods have notable influences on the absolute breakdown voltages, but do not affect the relative ranking of the liquids in terms of breakdown voltage. Lightning impulse breakdown voltages of ester liquids are generally comparable (less than 20% reduction) to that of mineral oil in a quasi-uniform electric field [9, 10].

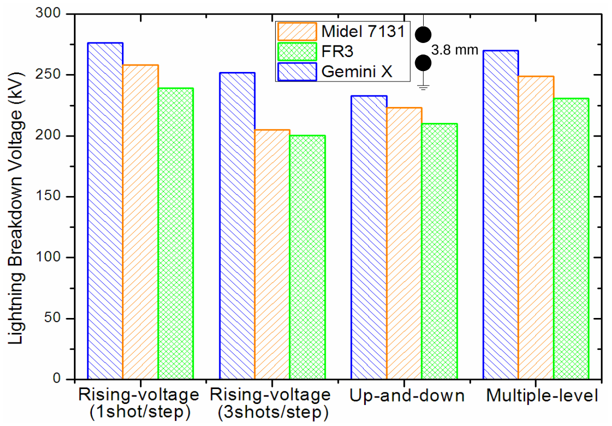
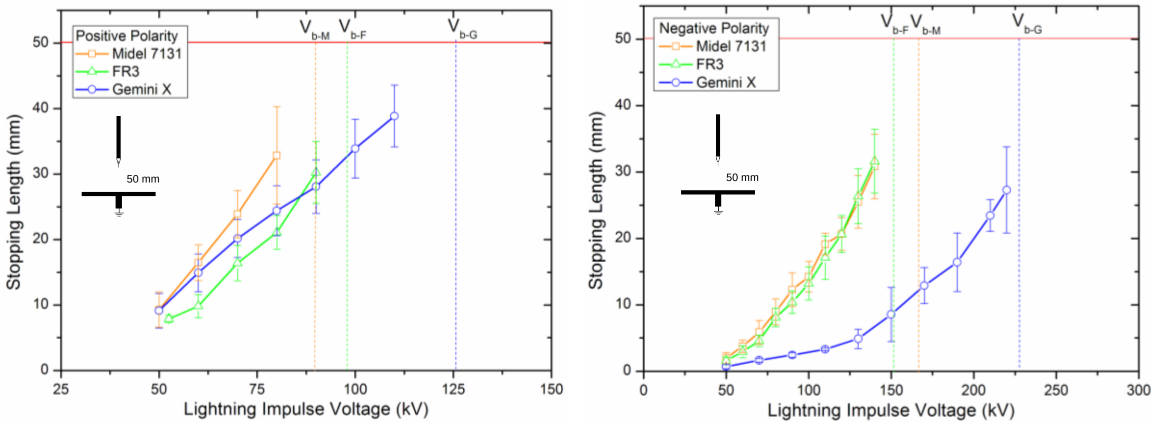


Figure 8. Comparison of lightning breakdown voltages between ester liquids and mineral oil using various testing methods; d=3.8 mm [10].

3.2. In non-uniform electric field

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 configuration (with a variable gap distance set to 50 mm for inception and propagation investigations). The tip radius of the needle electrode was guaranteed to be 50±5 μm. A high-speed camera was used to observe the inception and propagation of the streamer.

Inception voltages were determined by the first 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 9, 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 ester liquids are comparable to that of mineral oil, at about 50 kV, for this test condition.



(a) Positive polarity (b) Negative polarity

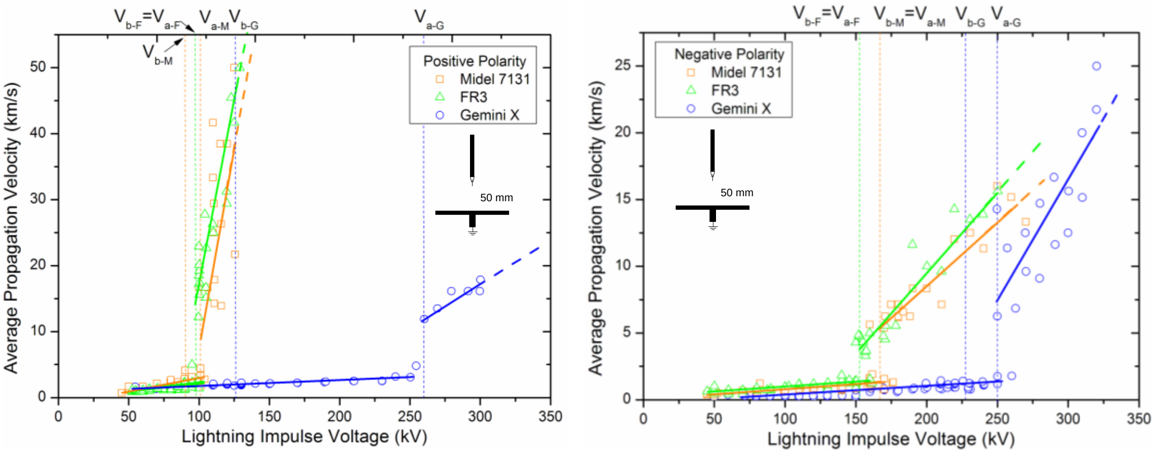
Figure 9. Streamer length in ester liquids under both positive and negative impulse voltages, d=50 mm, V_{b-M}, V_{b-F} and V_{b-G} indicate the 50% breakdown voltages of Midel 7131, FR3 and Gemini X respectively.

In terms of streamer length as shown in Figure 9, ester liquids 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 ester liquids 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 [31] under step-like impulse voltage. The negative streamer length of both ester liquids increases almost linearly with applied voltage from inception, following the same characteristic as under positive polarity but at a lower rate.

Figure 10 shows the average streamer velocity against voltage for the three liquids [32]. Before breakdown, the 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, the average velocity is determined as the 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 260 kV, 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 ester liquids increases much more quickly with voltage than in mineral oil.

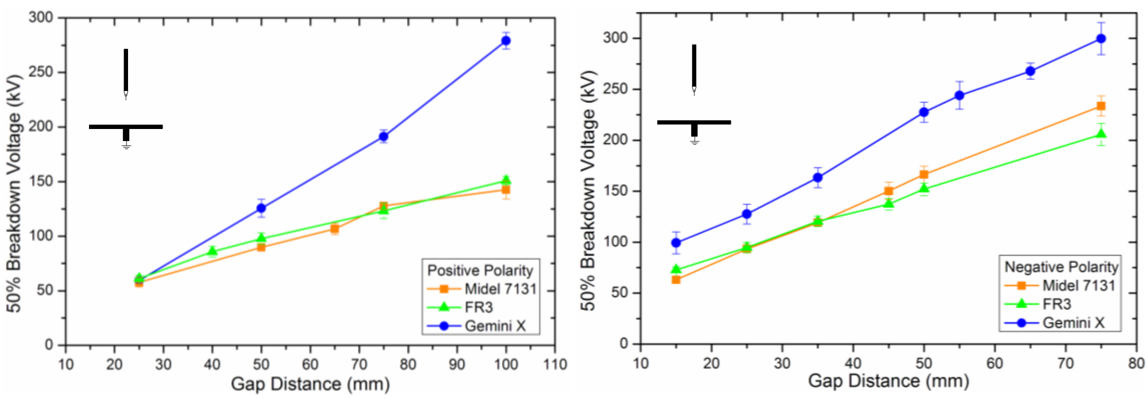
For negative polarity impulses, the acceleration voltage of mineral oil is similar to that for positive polarity at about 250 kV, the acceleration voltage for ester liquids is again lower, but the margin is narrower. The acceleration voltage of mineral oil is 1.6 times that of ester liquids. The velocity below the acceleration voltage is also lower for all three 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 10. 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 [32].

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 11 [32], under positive polarity, breakdown voltages at a 25 mm gap are almost identical for ester liquids and mineral oil. However with gap distances increased, both ester liquids show lower breakdown voltages than mineral oil. Under negative polarity, breakdown voltages of ester liquids 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 three liquids.



(a) Positive polarity (b) Negative polarity

Figure 11. Breakdown voltages of ester liquids under both positive and negative impulse voltages [32].

3.3. Influence of parallel pressboard

Figure 12 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) [33]. 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 a natural ester/pressboard interface. There is only a minor increase of stopping length at high 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 liquid gaps under both positive and negative polarities, as shown in Figure 13 [33]. A similar phenomenon was also reported at a gap distance of 100 mm under both polarities [12].

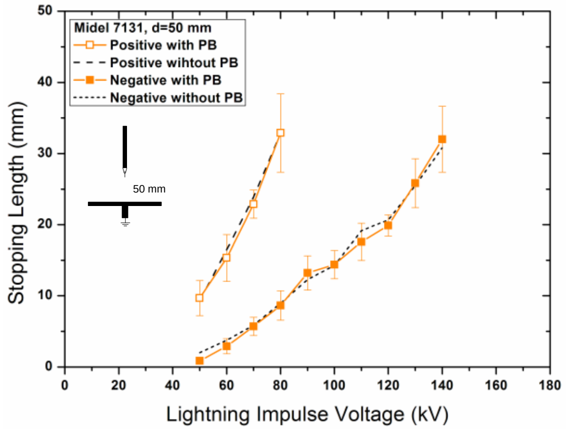
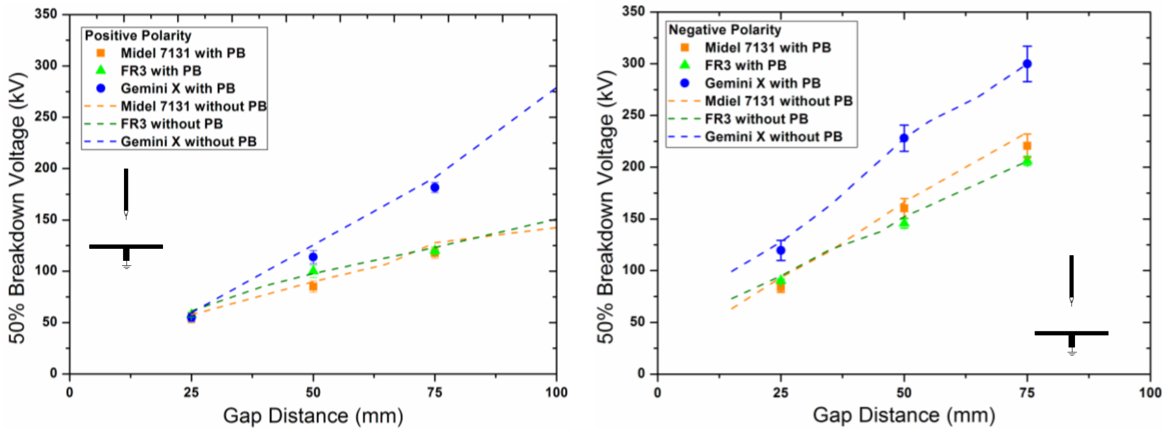


Figure 12. Influence of pressboard on streamer length under both positive and negative lightning impulse voltages, d=50 mm, Midel 7131 [33].



(a) Positive polarity (b) Negative polarity

Figure 13. Breakdown voltages on esters/pressboard interface under lightning impulse voltages [33].

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 a 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, as shown in Figure 14 [33].

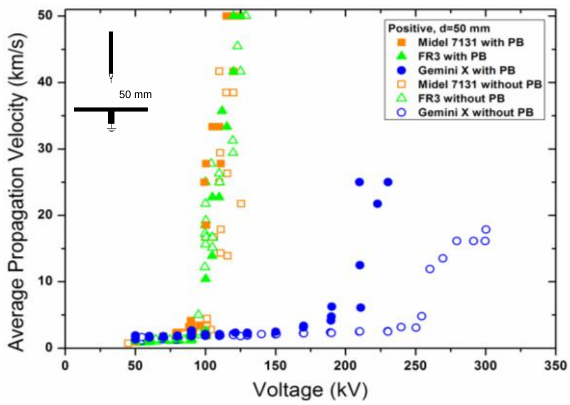


Figure 14. Influence of pressboard on streamer velocity under positive lightning impulse voltage, d=50 mm [33].

4. CONCLUSIONS

Experimental studies of the electrical performance of two ester liquids and a mineral oil used as benchmark were carried out in both quasi-uniform and non-uniform electric fields under AC and lightning impulse voltages respectively. Discharge inception, streamer propagation and breakdown in open gaps and on a liquid/pressboard interface were studied.

Under AC voltage, in a quasi-uniform electric field, the breakdown strength of ester liquids is similar to that of mineral oil for processed samples. Ester liquids are less sensitive to cellulose particle contamination than mineral oil, resulting in a higher breakdown voltage than mineral oil for highly contaminated samples. Breakdown voltages of both ester liquids and mineral oil start to decrease when the relative humidity is over ~20%. In a non-uniform electric field, the partial discharge inception voltage (PDIV) of ester liquids is close to that of mineral oil, irrespective of the presence of parallel pressboard or not. PD measurements at voltages higher than the PDIV show that the PD repetition rate (number per minute) for ester liquids increases much more quickly with voltage than in mineral oil. This is because ester liquids have more intense negative discharges. The introduction of parallel pressboard tends to promote creepage discharges especially in the negative voltage half cycles and enables more discharges to occur at smaller phase angles, in both ester liquids and mineral oil. The breakdown voltages of ester liquids subjected to a non-uniform electric field are lower than that of mineral oil.

Under lightning impulse voltage, the breakdown voltages of the ester liquids are comparable to that of mineral oil in a quasi-uniform electric field. Different test methods (rising-voltage, up-and-down and multiple-level methods.) have notable influences on the measured absolute breakdown voltages, but the ranking of the liquids in terms of breakdown voltage is not affected by the test method. In a non-uniform electric field, streamers in ester liquids propagate further and faster than those in mineral oil at the same voltage level; ester liquids have a much lower acceleration voltage indicating a lower tolerance to fast events than mineral oil. The presence of parallel 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. In general, breakdown voltages of ester liquids are lower than that of mineral oil in a non-uniform electric field, and the difference is increased at larger gap distances. To compensate for this volume effect, additional pressboard barriers (in a direction perpendicular to the field) may need to be added as partitions in large oil gaps in an ester filled power transformer.

Overall this work indicates that differences in electrical strength between ester liquids and mineral oil are most clearly shown in non-uniform electric fields. Discharge inception voltages are similar in all three liquids indicating that operational design stresses and therefore the basic size and configuration of an ester-filled transformer can be similar to that of a mineral oil filled unit. However once initiated, streamer propagation is generally faster and at lower voltages in ester liquids than in mineral oil, so the avoidance of discharge inception under both AC and impulse conditions is likely to be even more important for design and construction of ester filled power transformers in order to avoid breakdown, particularly under factory test stresses.

BIBLIOGRAPHY

[1] D. Martin, I.U. Khan, J. Dai and Z.D. Wang, "An overview of the suitability of vegetable oil dielectrics for use in large power transformers", Euro TechCon 2006, Chester, UK, pp. 4-23, 2006.
[2] S. Tenbohlen and M. Koch, "Aging performance and moisture solubility of vegetable oils for power transformers", IEEE Trans. Power Del., vol. 25, pp. 825-830, 2010.
[3] C. Perrier and A. Beroual, "Experimental investigations on insulating liquids for power transformers: Mineral, ester, and silicone oils", IEEE Electr. Insul. Mag., vol. 25, pp. 6-13, 2009.

[4] S. Arazoe, D. Saruhashi, Y. Sato, S. Yanabu, G. Ueta and S. Okabe, "Electrical characteristics of natural and synthetic insulating fluids", IEEE Trans. Dielectr. Electr. Insul., vol. 18, pp. 506-512, 2011.
[5] J. Dai and Z.D. Wang, "A comparison of the impregnation of cellulose insulation by ester and mineral oil", IEEE Trans. Dielectr. Electr. Insul., vol. 15, pp. 374-381, 2008.
[6] H. Borsi and E. Gockenbach, "Properties of ester liquid midel 7131 as an alternative liquid to mineral oil for transformers", Intern. Conf. Dielectr. Liquids (ICDL), Coimbra, Portugal, pp. 377-380, 2005.
[7] Y. Zelu, T. Paillat, G. Morin, C. Perrier and M. Saravolac, "Study on flow electrification hazards with ester oils", Intern. Conf. Dielectr. Liquids (ICDL), Trondheim, Norway, paper 13, 2011.
[8] X. Wang and Z.D. Wang, "Particle effect on breakdown voltage of mineral and ester based transformer oils", Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), Quebec, Canada, pp. 598-602, 2008.
[9] K. J. Rapp, J. Corkran, C. P. McShane and T. A. Prevost, "Lightning impulse testing of natural ester fluid gaps and insulation interfaces", IEEE Trans. Dielectr. Electr. Insul., vol. 16, pp. 1595-1603, 2009.
[10] Q. Liu, Z.D. Wang and F. Perrot, "Impulse breakdown voltages of ester-based transformer oils determined by using different test methods", Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), Virginia, US, pp. 608-612, 2009.
[11] C. T. Duy, O. Lesaint, A. Denat and N. Bonifaci, "Streamer propagation and breakdown in natural ester at high voltage", IEEE Trans. Dielectr. Electr. Insul., vol. 16, pp. 1582-1594, 2009.
[12] R. Liu, C. Tornkvist, V. Chandramouli, O. Girlanda and L. A. A. Pettersson, "Ester fluids as alternative for mineral oil: The difference in streamer velocity and LI breakdown voltage", Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), Virginia, US, pp. 543-548, 2009.
[13] D. Viet-Hung, A. Beroual and C. Perrier, "Comparative study of streamer phenomena in mineral, synthetic and natural ester oils under lightning impulse voltage", Intern. Conf. High Voltage Eng. and Applicat. (ICHVE), New Orleans, US, pp. 560-563, 2010.
[14] K. Miners, "Particles and moisture effect on dielectric strength of transformer oil using VDE electrodes", IEEE Trans. Power Apparatus Systems, vol. PAS-101, pp. 751-756, 1982.
[15] X. Wang, Z.D. Wang and J. Noakhes, "Motion of conductive particles and the effect on AC breakdown strengths of esters", Intern. Conf. Dielectr. Liquids (ICDL), Trondheim, Norway, paper 87, 2011.
[16] E. O. Forster, "Partial discharges and streamers in liquid dielectrics-the significance of the inception voltage", IEEE Trans. Dielectr. Electr. Insul., vol. 28, pp. 941-946, 1993.
[17] Z.D. Wang, Q. Liu, X. Wang, P. Jarman and G. Wilson, "Discussion on possible additions to IEC60897 and IEC61294 for insulating liquids tests", IET Electr. Power Appl., vol. 5, pp. 489-493, 2011.
[18] V. V. Sokolov, Z. Berler and V. Rashkes, "Effective methods of assessment of insulation system conditions in power transformers: a view based on practical experience", EIC, 1999.
[19] S. J. Fitton, "Surface discharges within oil insulated apparatus", IEE Colloquium on An Engineering Review of Liquid Insulation (Digest No. 1997/003), pp. 6/1-6/2, 1997.
[20] A. K. Lokhanin, G. Y. Shneider, V. V. Sokolov, V. M. Chornogotsky and T. I. Morozova, "Internal insulation failure mechanisms of HV equipment under service conditions", CIGRE Session, paper. 15-201, 2002.
[21] X. Yi, Z.D. Wang, F. Perrot and M. Lashbrook, "Surface treeing on pressboard barriers in synthetic and natural ester liquids under AC stress", Intern. Conf. Dielectr. Liquids (ICDL), Trondheim, Norway, paper 86, 2011.
[22] X. Yi and Z.D. Wang, "Creepage discharges along the interface between esters and pressboard", Euro TechCon, Chester, UK, 2010.
[23] J. Dai, Z.D. Wang and P. Jarman, "Creepage discharge on insulation barriers in aged power transformers", IEEE Trans. Dielectr. Electr. Insul., vol. 17, pp. 1327-1335, 2010.
[24] T. A. Prevost, "Dielectric Properties of Natural Esters and their Influence on Transformer Insulation System Design and Performance", IEEE PES Transmission and Distribution Conference and Exhibition, pp. 30-34, 2006.
[25] J. K. Nelson, "An assessment of the physical basis for the application of design criteria for dielectric structures", IEEE Trans. Dielectr. Electr. Insul., vol. 24, pp. 835-847, 1989.
[26] P. Rain and O. Lesaint, "A comparison of prebreakdown phenomena in mineral oil under step and AC voltages in divergent fields at large distances", Intern. Conf. Dielectr. Liquids (ICDL), pp. 259-263, 1993.
[27] P. Rain and O. Lesaint, "Prebreakdown phenomena in mineral oil under step and ac voltage in large-gap divergent fields", IEEE Trans. Dielectr. Electr. Insul., vol. 1, pp. 692-701, 1994.
[28] L. E. Lundgaard and O. Lesaint, "Discharges in liquids in point-plane gap under ac and impulse stress", Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), pp. 596-599, 1995.
[29] O. Lesaint, A. Saker, P. Gournay, R. Tobazeon, J. Aubin and M. Mailhot, "Streamer propagation and breakdown under ac voltage in very large oil gaps", IEEE Trans. Dielectr. Electr. Insul., vol. 5, pp. 351-359, 1998.
[30] X. Yi and Z.D. Wang, "Study on AC Creepage Discharge Patterns at the Interface of Natural Ester and Solid Insulations", Intern. Symposium of High Voltage Engineering (ISH), Hannover, Germany, paper D-029, 2011.
[31] G. Massala and O.Lesaint, "A comparison of negative and positive streamers in mineral oil at large gaps", Journal of physics. D, Applied physics, vol. 34, p. 1525, 2001.
[32] Q. Liu and Z.D. Wang, "Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage", IEEE Trans. Dielectr. Electr. Insul., vol. 18, pp. 285-294, 2011.
[33] Q. Liu and Z.D.Wang, "Streamer characteristic and breakdown in synthetic and natural ester transformer liquids with pressboard interface under lightning impulse voltage", IEEE Trans. Dielectr. Electr. Insul., vol. 18, pp. 1908-1917, 2011.