

INVESTIGATION OF IMPULSIVE BREAKDOWN OF INTERFACES FORMED BY ESTER INSULATING LIQUIDS AND SOLID DIELECTRICS

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Abstract

Due to the comparable dielectric behaviours, and significant enhancements in terms of environmental and safety performance, ester fluids are seen as a viable replacement for naphthenic liquids for use within insulating applications. In order to increase the adoption of ester liquids, and widen possible industrial applications, more extensive substantiation of their dielectric characteristics is required; particularly in how these dielectric liquids behave when exposed to impulse voltages. Furthermore, there is a lack of published work on how the breakdown properties of these liquids are altered when operating as part of a liquid-polymer insulation system. The present work details experiments conducted using impulse voltages of negative polarity to investigate the breakdown parameters (breakdown voltage and time to breakdown) of interfaces formed by dielectric liquids and a selection of polymer dielectrics. Samples of Nylon 66, Polymethylmethacrylate (PMMA), and Polyvinylidene difluoride (PVDF) were tested with: a synthetic ester, MIDEAL 7131; a natural ester, Envirotemp FR3; and a naphthenic liquid, Shell Diala S4 ZX (used for benchmarking). Experimental results from this work show that, under the studied test conditions, the solid-liquid interfaces formed by the selected solid dielectrics and ester fluids exhibit comparable dielectric strengths to those formed with the naphthenic oil under investigation.

I. INTRODUCTION

As environmental concerns and pressures grow, large industries have begun taking steps to actively mitigate the possibility, or severity, of the occurrence of an environmentally damaging event linked to their operations. One activity which presents such a hazard is the use of highly toxic mineral oils as the insulating medium within large electrical machines. As such, the power and pulsed power industries have undertaken extensive research into viable alternatives for this naphthenic dielectric fluid. In recent decades, ester based dielectric fluids have been shown to offer themselves as a possible replacement for mineral oils in typical insulating

applications such as transformer insulation and HV switchgear. This is as a result of ester liquids exhibiting similar dielectric strength to mineral oil under AC stress [1]. However, under impulse stress in highly divergent electric fields, some ester liquids demonstrate a lower breakdown voltage than that of naphthenic fluids [2,3]. Different factors may be responsible for this behavior of the ester liquids. Typically, the impulse breakdown process in a dielectric liquid is explained by streamer mechanisms. Pre-breakdown streamers (thin plasma/gas filled filaments) are formed in the liquid when stressed with electric fields above the streamer inception voltage. Lesaint [4] and Hebner [5] differentiated streamers based on their appearance and average propagation velocity. "Slow" streamers at the initial stage of the breakdown process/with lower applied voltages, with average velocities of a few km/s, were classified as mode 1, 2, and 3 streamers. Faster, modes 3 and 4, streamers, with average velocities of a few 10s km/s, occurred at the final stages of breakdown/with higher applied voltages, and their velocities were strongly dependent on the applied voltage.

The inability of ester fluids to resist the development of fast, '4th mode' streamers has been reported in [6]. It was experimentally shown that, within ester dielectric liquids, streamers quickly transition from the slower 2nd to the fast 4th mode both under both positive and negative impulsive stresses. This is attributed to the absence of polyaromatic molecules within the ester; compounds present within mineral oil which have been proven to inhibit streamer development [7].

Ester dielectric fluids, however, may offer enhancements in breakdown performance, as compared with mineral oils, in the case of high moisture content. In [8], it was observed that, as moisture content of the studied dielectric fluids increased, synthetic ester exhibited a comparable, at times superior, breakdown voltage to that of mineral oil. Furthermore, it has been shown in [9] that, due to their ability to operate with elevated moisture content, liquid-solid insulating systems which utilise ester as a liquid medium experience less degradation of the paper insulating material than a comparable system which employs mineral oil [9]. There is, however, a lack of published research on the

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performance of ester fluids within a liquid-polymer insulating system. This study addresses this gap, by investigating a number of liquid-solid insulating systems, comprised of an ester liquid and polymer dielectrics of varying relative permittivity. The experimental work reported in this paper examined the behavior of liquid-solid interfaces formed between natural ester, synthetic ester and mineral oil, and solid dielectrics, Nylon 66, Polymethylmethacrylate (PMMA) and Polyvinylidene fluoride (PVDF). These solid dielectrics have relative permittivity, ϵ_r , of 3.8, 3.5 and 7.4, respectively. The interfaces formed by combinations of these liquid and solid dielectrics were stressed with negative polarity impulses with key breakdown parameters (breakdown voltage and time to breakdown) logged for post-experimental statistical analysis.

II. EXPERIMENTAL SETUP

A schematic of the experimental setup utilised is shown in Fig. 1. Impulse voltages of the desired waveshape were provided through a 5-stage, air insulated Marx generator, connected to a 100 kV high voltage DC supply (Glassman, USA) with charging voltage set at 20 kV to achieve a nominal peak amplitude of the output signal of 100 kV.

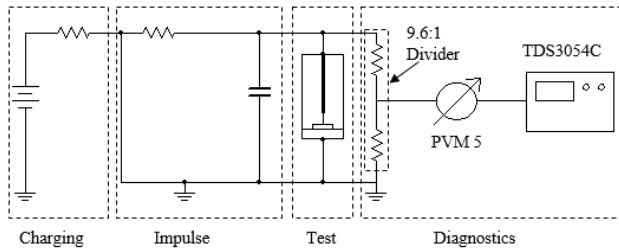


Figure 1. Experimental setup.

The desired impulse shape was achieved by employing two wave-shaping, front and tail, aqueous copper sulphate resistors. To limit the peak amplitude of any recorded voltage signals, a 9.6:1 voltage divider, consisting of a single flexible plastic tube, filled with water-CuSO₄ solution, was connected in parallel with the test cell. Voltage signals during breakdown were captured using a NorthStar PVM5 high voltage probe (80 MHz, 1000:1 division ratio) and recorded using a digitising oscilloscope (Textronix TDS3054C 500MHz, 5 Gs/s).

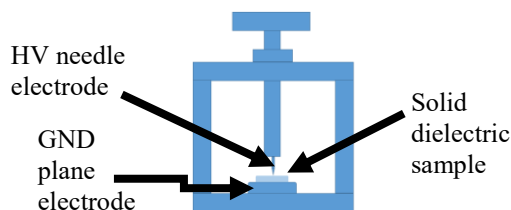


Figure 2. Test cell used in experimentation.

The test cell used in experimentation (Fig. 2) was manufactured from Perspex, with a total volume of ~500 ml. During experimentation, however, the volume of dielectric fluid used was limited to one 250 ml sample per experiment. This decision was taken to allow suitable breathability within the test cell; as the presence of this air gap would encourage any microbubbles present within the dielectric fluid, post-degassing or post-breakdown, to rise to the surface and, hence, limit any influence they may exert on breakdown mechanics.

A point-plane electrode geometry was chosen to generate the desired highly divergent electric field conditions. Consequently, a gramophone needle was used as the HV electrode, due to its well defined tip radius. As this radius is a key parameter in the development of a suitable field utilisation factor, the accuracy of manufacture of the needle tip was of paramount importance to ensure a comparative field was generated during all experiments. The ground electrode was of simple geometry; a 40 mm diameter mild steel plane electrode, with suitably rounded edges to limit field enhancement where possible. To mitigate the influence of surface asperities and contamination on breakdown dynamics, this electrode was polished prior to the commencement of any experimental works.

III. TESTING METHODOLOGY

The applied voltage impulse had a 7 μ s rise-time and 170 μ s fall time; this waveform was selected in the present study due to the lack of published experimentation using rise times longer than the standard lightning impulse waveshape front time of 1.2 μ s [4, 5]. The liquid-polymer insulating systems were exposed to such impulses of negative polarity, with the intention of achieving electrical breakdown on the wavefront of the applied impulses. Ten breakdown events were registered for a given insulating system, before both the liquid and solid dielectric samples were replaced, as well as the HV and ground electrodes. Then, another set of 10 breakdown events were recorded. This produced a dataset of 20 individual breakdowns for a given liquid-polymer combination; used to calculate mean, V_{BK} , values for each liquid-polymer insulating system investigated.

IV. DIELECTRICS UNDER INVESTIGATION

Within the present work, the dielectric strength of solid-liquid interfaces for three dielectric fluids were examined: mineral oil, Shell Diala S4 ZX; synthetic ester, MIDEL 7131; and natural ester, Envirottemp FR3. Key parameters of the investigated dielectric fluids are given in Table 1.

Table 1. Key parameters of examined dielectric fluids (adapted from [10]).

| | Shell Diala S4 ZX | MIDEL 7131 | Envirotemp FR3 |
|-----------------------------------|---------------------|-----------------------------|-------------------|
| Composition | Mix of hydrocarbons | Pentaerythritol tetra ester | Plant based ester |
| Degree of Biodegradability | Non | Highly | Highly |
| Oxidisation | Mildly susceptible | Non-susceptible | Susceptible |
| Water Saturation | 70 ppm | 2600 ppm | 1100 ppm |
| Flash Point | 191 °C | 260 °C | 316-330 °C |
| Relative Permittivity | 2.2 | 3.2 | 3.2 |
| Dielectric Strength (AC) | 60 kV | 75 kV | 56 kV |

From an operational perspective, it is evident that the ester fluids offer similar, if not improved, dielectric characteristics when compared to mineral oil. In the case of breakdown performance of solid-liquid interfaces, the higher relative permittivity of ester liquids may help to achieve improved dielectric performance; as a consequence of the smaller mismatch between the relative permittivity of the liquid and solid dielectrics. The higher water saturation level of esters liquids may also facilitate an improvement in insulating performance. It has been shown in previous experimental works that these higher moisture saturation levels can mitigate the aging effects experienced within the chosen solid dielectric, typically Kraft paper in this case [9], used in the composite insulating system. The use of ester fluids as liquid insulation will also allow the realisation of an improvement in operational safety; a result of the reduced combustibility and non-toxicity of these fluids.

Table 2. Key parameters of solid dielectrics (adapted from [11,12,13])

| | Nylon 66 | PMMA | PVDF |
|---------------------------------|------------------------|------------------------|------------------------|
| Composition | Polyamide | Polymethyl-metacrylate | Fluoropolymer |
| Density | 1.14 g/cm ³ | 1.19 g/cm ³ | 1.78 g/cm ³ |
| Dielectric Strength (AC) | 27 kV/mm | 20 kV/mm | 18 kV/mm |
| Relative Permittivity | 3.8 | 3.5 | 7.4 |
| Surface Resistivity | >10 ¹³ Ω | >10 ¹³ Ω | >10 ¹³ Ω |

Table 2 details the key parameters of the polymer dielectrics used within the experimental works. The main criterion in the selection of these materials was their relative permittivity. Care was taken in selecting, usable, materials which possess relative permittivity values close to that of the examined ester fluid ($\epsilon_r \sim 3.2$). As a result, Nylon 66 and PMMA, relative permittivity 3.8 and 3.5 respectively, were selected for examination. A third

material, PVDF, was chosen for comparison, as it has a relative permittivity twice that of the studied ester dielectrics. This material was selected in order to better understand how large discrepancies in relative permittivity can affect the breakdown behaviour of ester liquid-polymer insulating systems. The solid dielectric samples were in the form of “pucks” (diameter of 20 mm thickness of 6 mm). The thickness was chosen as the best compromise between ensuring suitable bulk dielectric strength, and setting the propagation distance such that any streamers propagating across the liquid-solid interface could reach ground. Prior to the breakdown tests, ‘rings’ visible on the surface of the dielectric, produced during fabrication of samples, were removed by employing an abrasive surface treatment, with the samples placed in a vibrating tumbler for ~24 hrs. This provided smoother solid dielectric surfaces, with manufacturing marks almost completely removed, and thus limiting any influence surface asperities may have had on dielectric breakdown. Suitably smoothed samples were then cleaned using ethanol to remove surface contamination, before being immersed in the dielectric fluid. To ensure satisfactory mitigation of the presence, and influence, of microbubbles within the liquid dielectric, the filled test cell was placed inside a vacuum chamber to degas for 30 minutes prior to any experiments being conducted.

V. EXPERIMENTAL RESULTS

Upon commencement of the initial breakdown tests involving liquid-solid interfaces formed with PVDF as the solid insulating medium, it was found that the PVDF samples were experiencing bulk breakdown rather than the desired surface flashover. Therefore, the experimental results for PVDF will not be discussed at this time.

Under the chosen impulse conditions, it is evident that the interfaces between samples of both types of solid and naphthenic oil outperform the interfaces formed between ester fluids and the solids.

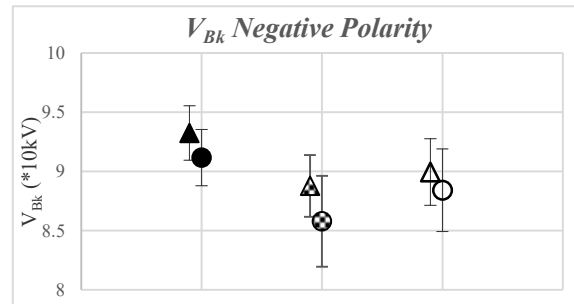


Figure 3. Recorded negative polarity breakdown voltage values. Δ: Nylon, ○: PMMA. Open shapes: FR3, solid shapes: Shell Diala and patterned shapes: MIDEL 7131. Error bars represent standard deviation values.

The naphthenic oil/solid interfaces demonstrated ~5% higher mean breakdown voltage as compared with the interfaces formed by ester liquids and the same solid materials. For all of the liquids, nylon appears to have a slightly higher value of surface breakdown voltage than PMMA. Nylon has a higher bulk breakdown strength than PMMA, but it is not clear how this would affect the surface breakdown strength. There is also a difference in the relative permittivity of the materials, which may affect the distribution of the electric fields across the surface of the polymer. However, it should be noted that the standard deviation of the experimental results, shown as the error bars in Fig. 3, indicates that this observation may not be statistically significant.

When comparing the experimental results gathered for interfaces formed by the individual solid dielectrics and the two investigated ester dielectric fluids, given the large deviation in measured values of breakdown voltage, it cannot be said that any discernible statistically significant difference exists between the dielectric strengths of these liquid-polymer insulating systems.

From the experimental results presented in this work, it can be said that, under these test conditions, both natural and synthetic ester fluids offer comparable dielectric performance to that of conventional naphthenic oils, when acting as part of a liquid-solid insulating system in conjunction with the polymer dielectrics investigated.

VI. CONCLUSION

Analysis of the experimental results has shown that, under the specific test conditions used in the present study, the interfaces formed between the chosen ester fluids and solid dielectrics exhibit similar dielectric performance to the interfaces formed by the same solid dielectrics and the selected naphthenic oil. No statistically significant difference was observed between the breakdown voltages of a given solid dielectric when immersed in varying dielectric fluids; likewise, there is no statistically significant difference in dielectric strength of a given liquid when used to form an interface with any of the polymer dielectrics studied in this work.

Interfaces comprising the chosen naphthenic oil appear to consistently exhibit the highest dielectric strength, regardless of the polymer utilised within the liquid-solid system. The observed phenomenon resulting in the bulk dielectric breakdown of the PVDF samples will require further investigation, in order to fully substantiate its origin. Furthermore, as all of the tests were conducted with liquids in an 'As Received' condition (as supplied by the manufacturer), work is planned to evaluate how elevated moisture levels will affect the dielectric performance of the examined liquid-solid insulating systems. At this time, it is difficult to fully validate whether the dielectric behaviour of esters is comparable to

that of mineral oil. However, based on these experimental works it can be said, in part, that natural and synthetic esters offer similar insulating properties to those of naphthenic fluids, when operating as part of a liquid-polymer insulating system.

VII. REFERENCES

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