

BREAKDOWN CHARACTERISTICS OF NATURAL AND SYNTHETIC ESTER LIQUIDS WHEN CONTAINING VARYING LEVELS OF MOISTURE

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Abstract

Ester insulating liquids provide a number of benefits when compared with conventional naphthenic oils. To increase acceptance of esters as a long term replacement for mineral oils in high voltage/pulsed power systems, it is of paramount importance that their dielectric properties are well known. This paper examines the breakdown voltage, and time to breakdown, of MIDEL 7131 synthetic ester, the natural ester Envirotemp FR3 and a mineral oil: Shell Diala S4 ZX, at varying levels of moisture saturation, when exposed to HV impulses of both positive and negative polarity. No statistically significant difference in the breakdown voltage of the ester liquids with increasing relative humidity for either polarity was observed. Noticeable polarity dependence in breakdown voltage values was observed with Envirotemp FR3 liquid, which possesses the highest breakdown strength under positive impulses, but the lowest under negative impulses. Inversely, MIDEL 7131 exhibits the lowest breakdown voltage for positive impulses, and the highest breakdown voltage under negative impulsive energisation.

I. INTRODUCTION

The classification of naphthenic oil as a Class 1 water hazard has caused industry to begin research works focusing on new, more environmentally friendly, insulating liquids that can act as a replacement for these naphthenic oils. Both natural and synthetic ester liquids have been shown to present a viable alternative to currently used naphthenic insulating oils for both power and pulsed power applications, [1-2]. This is mainly due to the similarities that exist between the liquids in terms of dielectric characteristics. Ester liquids also present a number of other benefits in comparison to naphthenic oils, such as biodegradability, significantly lower toxicity, improved fire safety due the higher flash point, and an enhanced ability to operate in the presence of moisture, attributed to the increased saturation point of ester liquids.

In [3], it is demonstrated that, when under AC stress, both natural and synthetic ester liquids exhibit a higher breakdown voltage than naphthenic mineral oil, although a higher standard deviation was observed in the ester samples. Consequently, it was concluded that there is no discernible difference between esters and mineral oil in terms of breakdown voltage when exposed to AC stress. This, however, is not replicated under impulse conditions, where [4] and [5] show that, when exposed to lightning impulses, ester liquids typically exhibit a lower mean breakdown voltage than mineral oils. These disparities in the breakdown voltage of ester liquids and mineral oils are also seen to worsen under high field inhomogeneity and in longer inter-electrode gaps. Polarity has also been shown to affect breakdown voltage of esters, with typical values for negative impulse breakdown voltages being higher than for positive impulsive stresses [4], [6]. The breakdown voltage of an insulating liquid will also be affected by the amount of moisture contained within the liquid. In [7], it was observed that both ester and naphthenic liquids experience a reduction in breakdown voltage as their relative moisture content increases. The specific reduction in breakdown voltage varies with the type of liquid and its composition. Aspects not addressed in [7] include how field divergence influences this reduction in breakdown voltage, as well as any affect voltage polarity may have on the reduction experienced.

The present paper reports on experimental results obtained using three dielectric fluids: synthetic ester MIDEL 7131; natural ester Envirotemp FR3, and a naphthenic mineral oil: Shell Diala S4 ZX. The study is focused on the behavior of the three liquids with different moisture contents: the ‘As Received’ liquid state, which classifies liquid that has been taken from newly opened containers provided by the manufacturer; the ‘Naturally Aged’ liquid state, which refers to liquid exposed to ambient laboratory air, allowing moisture content to come into equilibrium with the relative humidity of the laboratory air (typically 35%RH); and the ‘Accelerated Aged’ liquid state, where liquid samples underwent intensive humidification to increase water content, up to ~70%RH. The liquid samples were stressed with 7/170 μ s impulses, of both positive and negative polarity, with

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breakdown voltage and time to breakdown recorded for the purpose of statistical analysis.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The pulsed power supply consists of a five stage, air insulated, inverting Marx generator, powered by a high voltage direct current (HVDC) source (100kV, Glassman Inc. USA), including a chain of charging resistors connected in series between the HVDC source and the Marx, and wave-shaping resistors.

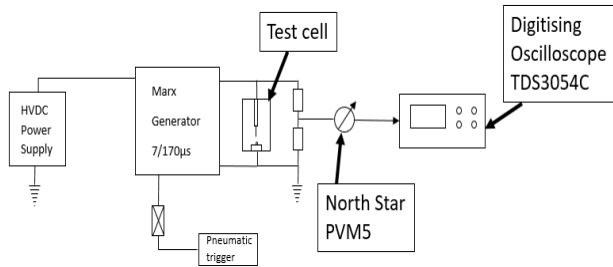


Figure 1. Experimental setup.

The front wave-shaping resistor, with a resistance of 14 k Ω , is used to achieve impulses with a 7 μ s rise time; this resistor consists of a tube filled with an aqueous copper sulphate (CuSO₄) solution. In order to ensure that the peak voltage was limited to a suitable level for the chosen measurement equipment, a custom built voltage divider, which consists of a column filled with aqueous CuSO₄ solution (9.6:1 division ratio), was connected in parallel with the test cell. The output of this divider was connected to a commercial HV divider (Northstar PVM-5 80 MHz nominal bandwidth, 1000:1 division ratio) and the voltage wave-forms were recorded using a Tektronix TDS3054C oscilloscope (500 MHz 5 Gs/s).

The ambient air humidity and relative humidity of the insulating liquid samples, as well as the ambient temperature at the time of testing, were measured using an Omniport 20 humidity and temperature probe.

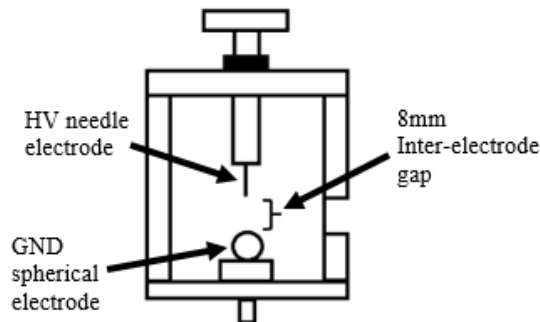


Figure 2. Test cell used in experimentation.

The breakdown test cell (Fig. 2) was constructed from glass reinforced nylon and has an inner diameter of 55 mm and a total volume of ~150 ml. To ensure the development of highly divergent electric field conditions, gramophone needles were utilised as HV electrodes. As a gramophone needle has a well-defined tip radius, it can be assured that the use of such a needle will guarantee the development of the required consistency in field divergence. Mild steel ball bearings of diameter 12.6 mm, obtained from Rapid Electronics, were used as ground electrodes. The ground electrode was fixed in place using a magnetic holder. Implementation of this point-sphere topology in the current experimental system facilitated the realisation of a field utilisation factor of $\eta \sim 0.01$.

III. TESTING METHODOLOGY

The following six steps were implemented in each round of breakdown tests:

1. Cleaning of test cell – this was done using pure ethanol with 5 minutes allotted post-cleaning to allow residual ethanol to evaporate.
2. Replacement and cleaning of electrodes – before each test a new pair of electrodes were chosen and cleaned with ethanol.
3. Measurement of ambient air and liquid sample relative humidity – the moisture content of the sample was taken prior to it being used in the impulse tests.
4. Fill test cell with liquid – The same volume of liquid (150 ml) was used for each round of tests.
5. Removal of residual gas bubbles – the test cell was placed within a vacuum chamber for 30 minutes prior to any test being conducted to ensure no gas bubbles were present.
6. Performing of the impulse test – The chosen charging voltage for the Marx generator was 30 kV DC. This produced a nominal peak output voltage of 150 kV. During a single round of tests, 10 breakdown events were performed. After the occurrence of 10 breakdowns, the liquid sample as well as the HV (needle) and ground (ball bearing) electrodes were replaced.

IV. LIQUIDS USED IN EXPERIMENTATION

Three dielectric fluids were examined within the experimental work; the naphthenic liquid Shell Diala S4 ZX (used as a benchmark for the dielectric performance of mineral oil), synthetic ester MIDEL 7131 and the

natural ester Envirotemp FR3. These ester liquids were selected for this study as they are both used within the power industry as a dielectric media in both distribution and power transformers, and may provide equivalent, or superior, dielectric performance to mineral oil. Thus, these dielectric liquids may potentially be considered as a viable environmentally friendly and fire-resistant alternative to naphthenic mineral oils.

Table 1. Key parameters of examined dielectric fluids (adapted from [8]).

	Shell Dials S4 ZX	MIDEL 7131	Envirotemp FR3
Composition	Mix of hydro-carbons	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
Permittivity	2.2	3.2	3.2
Dielectric strength (AC)	60 kV	75 kV	56 kV

Table 1 details some of the key parameters of the chosen dielectric liquids being investigated. As can be observed, esters, both natural and synthetic, offer a number of benefits when compared to naphthenic liquids; i.e. high degree of biodegradability and an improved safety profile; due to their reduced combustibility. Ester liquids also have significantly higher moisture saturation levels as compared with mineral oils. Thus, given the well documented sensitivity of the breakdown voltage of naphthenic liquids to their moisture content, higher moisture saturation levels may offer an improvement in operational performance, were these alternative fluids to be adopted as a replacement for mineral oils in insulating applications.

In order to evaluate how the breakdown performance of the chosen ester fluids is affected by the relative humidity of the liquid, three different levels of moisture content were examined. The first of these was ‘As Received’ liquid, which categorises liquids used in the condition that they were provided by the manufacturer (lowest %RH values). Another state investigated was ‘Naturally Aged’ liquid, where liquid containers were left open within the laboratory to allow moisture levels to rise to equilibrium with ambient conditions (medium %RH values). The final examined state of saturation was ‘Accelerated Aged’ liquid, liquids in this state were subjected to a process of humidification, in order to

increase moisture saturation levels significantly over a short period of time (highest %RH values).

Table 2. Relative moisture levels for a given state.

Liquid	As Received		Naturally Aged		Accelerated Aged	
	RH	ppm	RH	ppm	RH	ppm
Shell Dials	21%	15	35%	25	70%	49
Midel 7131	12.5%	325	34%	884	72%	1872
FR3	9%	99	34%	374	73%	803

The specific levels of relative humidity associated with each liquid state are shown in Table 2. It is clear that ester liquids offer much higher moisture absorption, due to their higher water saturation points; clearly substantiated here, as even the lowest level of moisture content observed for the esters within these tests (~99 ppm for the ‘As Received’ natural ester) is still ~1.4 times higher than the water saturation level of mineral oil (70 ppm). This characteristic of ester liquids can offer performance enhancements with respect to breakdown voltage, since the water content plays a significant role in the breakdown mechanisms of dielectric liquids [9].

Three individual samples were used for each humidity condition for a given dielectric fluid, with 10 breakdown events measured for each sample. This resulted in the recording of thirty individual breakdown events for a given state of moisture level for each of the studied dielectric fluids. This allowed for the statistical analysis of the measured breakdown parameters: breakdown voltage and time to breakdown.

Significant research works already exist in relation to the performance of dielectric liquids under standard lightning impulse voltages (1.2/50 μ s) [4], [5], [10], and [11]. However, there is a lack of published research on how esters perform under non-standard voltage waveforms. Therefore, a voltage wave-shape with significantly longer rise-time, 7 μ s, was used in the present work, the liquid dielectric samples being stressed with 7/170 μ s impulses. Both positive and negative impulses were used, with the aim of determining the influence that polarity exerts on the breakdown mechanisms of the chosen ester fluids, and how this compares to that of the chosen naphthenic liquid.

V. EXPERIMENTAL RESULTS

Due to parasitic inductance in the pulsed power circuit, the voltage waveforms were subjected to a de-noising procedure, in order to identify accurately both parameters,

time to breakdown and breakdown voltage. Thus, all experimental waveforms were fitted with an exponential function, Eq. (1), using Origin Pro graphing software.

$$V(t) = V_0 \exp\left(-\frac{t}{t_0}\right) + V_{Offset} \quad (1)$$

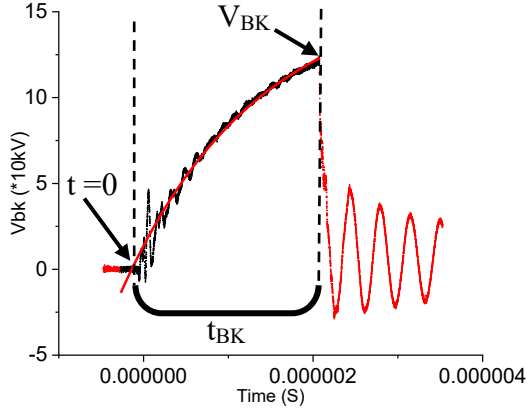


Figure 3. Exponential fitting process implemented using Origin graphing software.

Fig. 3 shows an example of the fitting of Eq. (1) to the pre-breakdown part of the experimental voltage waveform. The measured breakdown voltage was taken from the value of the exponential part of the curve at the point of breakdown. The time to breakdown for a given voltage signal was taken from the point at which the fitting line, Eq. (1) crosses zero on the horizontal line (which was taken as $t=0$ in this analysis), to the time instant at which the voltage collapses (which corresponds to the point of breakdown). This method of obtaining breakdown voltage and time to breakdown was applied to all waveforms recorded during experimentation.

A. Positive Polarity Results

When exposed to positive polarity impulses, the studied synthetic ester liquid, MIDEL 7131, demonstrated a reduction in breakdown voltage after the first breakdown event. A reduction of $\sim 30\%$ was observed in measured breakdown voltage when comparing the first recorded value to the subsequent values. Consequently, the presented results do not take account of this initial breakdown; with mean values calculated omitting the values recorded during this first breakdown of the liquid sample. To ensure comparability of results, this process of neglecting the first recorded breakdown was applied to all samples of the investigated dielectric fluids.

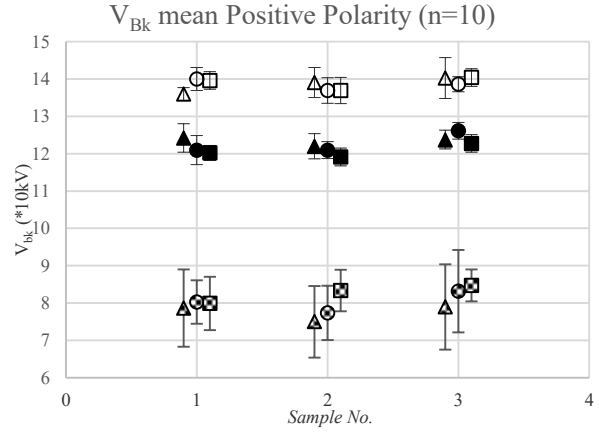


Figure 4. Recorded positive polarity breakdown voltage values. Δ : 'As Received', \circ : 'Naturally Aged' and \square : 'Accelerated Aged'. Open shapes represent FR3, solid shapes detail Shell Diala and patterned shapes MIDEL 7131. Error bars represent standard deviation values.

Fig. 4 details the mean breakdown voltage for each given sample for a particular moisture level ($n=10$). As Fig. 4 shows, there exists no statistically significant difference between breakdown voltages at given states of moisture levels for a given liquid.

No statistically significant cross-sample variations are observed when comparing breakdown voltages for the varying moisture levels of a given dielectric liquid, as can be seen from the overlap of the error bars which represent standard deviation values. This may suggest that the dominant mechanism driving breakdown under this impulsive regime is the process of the development of fast ionization front(s), rather than bubble formation through local Joule heating of the liquid. As stated in [12], the ionization front (streamer) velocities in highly non-uniform field topologies are related to the electric field strength. Higher streamer velocities may result in lower impulsive strength of the dielectric liquid.

Differences in dielectric behaviour do exist when comparing the types of dielectric fluid. For positive impulses, the chosen natural ester exhibits the highest values of breakdown voltage across all examined liquid states. The synthetic ester demonstrated the worst breakdown performance of the three studied liquids under positive impulse stress, with breakdown consistently occurring at a lower voltage than that of the other examined dielectric liquids.

Recorded breakdown voltage values for the natural ester are, on average, ~ 1.7 and ~ 1.2 times higher than those for the synthetic ester and mineral oil, respectively. This demonstrates that, under these experimental conditions, and when exposed to positive polarity impulses, the chosen natural ester can be considered as comparable, even outperforming, the examined naphthenic oil. The synthetic ester investigated is seen to have the lowest breakdown voltages under these

impulsive conditions. These low breakdown voltage values can be attributed, in part, to a reduction in dielectric strength after the first breakdown: the breakdown voltage is observed to reduce by ~30% post-first breakdown. This phenomenon was only observed after the initial breakdown and, as such, is not cumulative. Consequently, more investigation of this dielectric fluid is required to allow full substantiation of its dielectric characteristics under these impulsive voltage regimes.

When evaluating the effect that moisture level has on the dielectric properties of the chosen esters, it can be seen that the synthetic ester does experience a marginal increase in dielectric strength as water levels increase. The observed increase, given the high divergence in measured breakdown voltage values, is not statistically significant. Therefore, in order to fully understand the fundamental dielectric characteristics in impulsive regimes, further experimental work will be required.

B. Negative Polarity Results

When analysing the obtained values of breakdown voltage for the dielectric liquids under negative polarity impulses, it is again apparent that no statistically significant variation exists between mean sample values for a given state for a particular dielectric liquid. Under these conditions, the synthetic ester exhibited the highest breakdown voltages across all samples, for all liquid conditions (for different moisture levels). Also, the reduction in breakdown voltage observed after the initial shot during positive impulse exposure did not occur for negative polarity.

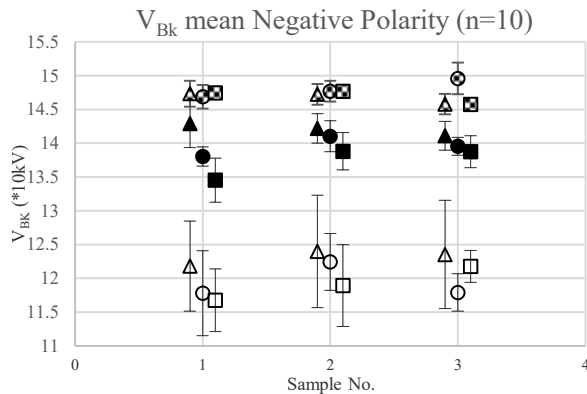


Figure 5. Recorded negative polarity breakdown voltage values. Δ : 'As Received', \circ : 'Naturally Aged' and \square : 'Accelerated Aged'. Open shapes represent FR3, solid shapes detail Shell Diala and patterned shapes MIDEL 7131. Error bars represent standard deviation values.

As seen in Fig. 5, breakdown voltage follows a similar trend to that described in previously published papers: i.e. as moisture saturation increases, breakdown voltage will decrease. A single increase was measured for MIDEL when comparing 'As Received' to 'Naturally Aged'

samples, thought to be as a result of the significantly higher moisture saturation point of the fluid. It was observed that moisture level exerts an influence on the variability of breakdown voltage, with divergence in measured breakdown values becoming more consistent as moisture level increases.

C. Experimental Findings

When analysing the obtained breakdown values for both polarities, it is evident that a strong polarity dependency exists in the dielectric breakdown behaviour of the examined ester liquids. Both esters demonstrate opposing behaviours for a given polarity of impulse. Under positive impulse stress, the natural ester outperforms both the naphthenic liquid and the synthetic ester fluid. The inverse was observed when examining the results obtained from negative impulse experimentation.

As would be expected, the breakdown voltage of mineral oil used in this experimental work follows the trends described in [4], [5], [13], [14], in that the breakdown voltage is higher under negative energisation. The experimental results confirm that the synthetic ester also exhibits such behaviour. However, in the case of FR3 natural ester, the breakdown voltage for negative energisation was lower than the breakdown voltage for positive energisation. Similar results are reported in [15], where a number of electrode topologies were examined. In [15], FR3 natural ester exhibited a similar (to that observed in this experimental work) behaviour in its dielectric performance; i.e. higher breakdown voltages when exposed to positive impulses.

When accounting for how moisture can affect the dielectric strength of the chosen ester fluids, it is evident that, under positive polarity, both experience a small increase in breakdown voltage with heightened moisture saturation. Although this increase is not statistically significant, this rise in breakdown strength corresponds to a reduced standard deviation. The largest variations in positive and negative breakdown voltage were observed when comparing those obtained for the synthetic ester. It was found that negative breakdown voltage values were ~2 times higher than positive breakdown voltages. This is as a consequence of the reduction in dielectric strength observed after the first shot (first breakdown event in liquid sample). Further investigation is required to elucidate what is the main reason for such a significant reduction of the breakdown voltage after the first positive impulse.

No significant carbonisation of either the fluid or electrodes was observed during any of the breakdown experiments where one of the esters formed the test liquid. The only degradation observed was a mild discolouration of the fluid, however no residuals were observed after visual examination of the breakdown test cell. This was different from the behavior of the naphthenic fluid, where, upon completion of a round of 10 breakdown tests, considerable amounts of carbon had to

be removed from the test cell and electrode housings. Further work is planned to examine the post-breakdown fluid samples using spectroscopy techniques, in order to determine their post-breakdown composition, and allow for further understanding of the dielectric characteristics of these unconventional dielectric fluids.

VI. CONCLUSIONS

Based on the experimental results obtained in the present work, it has been established that ester fluids MIDEL 7131 and FR3 exhibit comparable dielectric performance to naphthenic oil Shell Diala S4 under the applied test conditions. The natural ester FR3 exhibits the highest dielectric strength under positive impulses, but the lowest when negative polarity voltages were applied. The opposite is true for the chosen synthetic ester MIDEL 7131, which demonstrates the highest breakdown voltages under negative energisation, and the lowest under positive voltage stress. The chosen ester fluids were observed to have a higher breakdown voltage as their moisture content increased, in contrast to the studied naphthenic liquid Shell Diala S4, which demonstrated a reduction in dielectric strength as its moisture content increased. The variation in measured breakdown voltage values for the ester fluids also reduced as relative moisture content increased. Based on the experimental results, it can also be postulated that the studied ester liquids offer comparable, and in some cases superior, dielectric performance to that of the chosen naphthenic liquid. At this time, however, further investigation and experimentation is required to fully understand the mechanisms which govern the dielectric performance of these fluids.

VII. REFERENCES

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