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Vermeer, Mischa; Niasar, Mohamad Ghaffarian; Wielen, Peter Van Der; Born, Dennis Van Der; Vaessen, Peter

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# Frequency and Distance Dependency of Synthetic Ester Breakdown Voltage


Mischa Vermeer
Electrical Energy Systems
Technical University of Eindhoven
The Netherlands
m.e.vermeer@tue.nl

Mohamad Ghaffarian Niasar
High Voltage Technologies
Technical University of Delft
The Netherlands
M.GhaffarianNiasar@tudelft.nl

Peter van der Wielen
Electrical Energy Systems
Technical University of Eindhoven
The Netherlands
p.c.j.m.v.d.wielen@tue.nl

Dennis van der Born
High Voltage Technologies
Technical University of Delft
The Netherlands
D.vanderBorn-2@tudelft.nl

Peter Vaessen
High Voltage Technologies
Technical University of Delft
The Netherlands
P.T.M.Vaessen@tudelft.nl


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***Abstract*—Due to climate change more power converters are installed in the grid resulting in the injection of (supra-) harmonic currents and voltages in the grid. As part of a larger research, the impact of harmonic frequencies on insulation materials is studied. This paper discusses the results of breakdown voltage tests of synthetic ester liquid with varying frequency and electrode distance. A test cell according to IEC 60156 is used with electrode distance varying from 0.5 mm to 0.1 mm and the frequency is varied from 50 Hz to 2000 Hz. The results indicate a dependency on both electrode distance and fundamental frequency.**



***Keywords*—Synthetic ester, IEC 60156, Breakdown voltage, Electrode distance, Frequency**


## I. Introduction

In the attempt to limit climate change, the energy transition has started to transfer from fossil energy resources towards renewable energy resources such as wind and solar. Additionally, the energy sources for transportation are shifting towards battery charged vehicles. These technologies are using power electronic convertors and despite filtering, it has been noted that these technologies involve current and voltage distortions in the supraharmonic spectrum (2-150 kHz). This study is part of a larger study that researches the impact of (supra)harmonics on the lifetime of dielectric insulation materials.

To investigate the frequency dependency of the breakdown voltage in solid insulation materials like XLPE, a test setup according to IEC 60243 is used. However, due to the very high breakdown strength of XLPE (much higher than 100 kV/mm) a surrounding medium is required that can withstand these electric fields to minimize the edge effect on the triple point of the electrode. The standard prescribes transformer oil for samples with high electric breakdown voltage. However, experience and literature [1] show that this medium is insufficient for preventing premature breakdown at the triple point due to partial discharges in the oil at the triple point, prior to the breakdown of the sample (Other samples are used with lower breakdown voltage than XLPE). This negatively influences the tests, because in these situations the edge effect, with its partial discharges in the oil, is measured instead of the XLPE dielectric strength. In search for improvements, synthetic esters show better results due to higher permittivity and higher breakdown strength if dried. During initial experiments the synthetic ester shows better results. It is observed that for 1 kHz the breakdown location could be manifested at the homogeneous area between the electrodes, rather than at the triple point. On the contrary, at 50 Hz, the breakdown position remained at the triple point, indicating that for 50 Hz the breakdown strength of the synthetic ester was still insufficient. It was also noted that the XLPE breakdown voltage at 1 kHz was substantially lower than at 50 Hz and this raises the question how the breakdown strength of synthetic esters behaves under various frequencies.

## II. Test setup and procedure

In this study the breakdown voltage of synthetic ester liquid Midel 7131 is tested on various frequencies (50 Hz, 300 Hz and 2 kHz) and electrode distances (0.1 mm to 0.5 mm). The liquid is vacuumed and dried for 14 hours before testing, assuring maximum breakdown voltage. The breakdown voltage is tested according to IEC 60156. However, the number of breakdown tests per setup is increased to 20 instead of 6 to ensure a more reproducible result.

The following test setup is used, as shown in figure 1. An arbitrary waveform generator in combination with an arbitrary wave power amplifier with voltage rating +/- 30kV is used as power source. The arbitrary wave generator is set to a sinusoidal waveform with the desired frequency and with a ramp up amplitude modulation resulting in an output voltage of the amplifier with a 2 kV/s voltage increase with a maximum voltage of 19 $kV_{rms}$ due to the rating limits of the power amplifier. To protect the amplifier a series resistor of 50 kΩ is used in combination with two support insulators, which both have an internal capacitance of 50 pF. A standard breakdown voltage test cell is used with partially spherical electrodes with 25 mm radius and diameter of 36 mm. The internal voltage and current measurement of the power amplifier in combination with a digital oscilloscope is used for the actual measurements. The actual applied voltage is calculated by compensating for the voltage drop over the resistor.

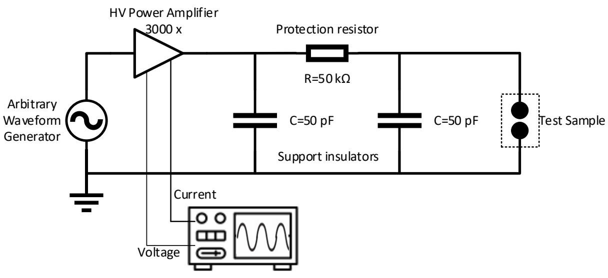


Fig. 1. Test setup

After breakdown, gas bubbles will occur between the electrodes. The standard prescribes mechanical stirring to dissolve these gas bubbles. However, experience shows that this method is insufficient for the setup with these small electrode distances. Therefore, manual cleaning in combination with stirring is applied to remove the gas bubbles prior to the next breakdown test. Figure 2 shows an example of air bubbles between the electrodes after a breakdown.

Due to the limited voltage output of the power amplifier not all breakdown tests, specifically at larger distances and frequencies, resulted in a successful breakdown. In such cases the maximum voltage is recorded as no breakdown, after which the test procedure continued as described above.

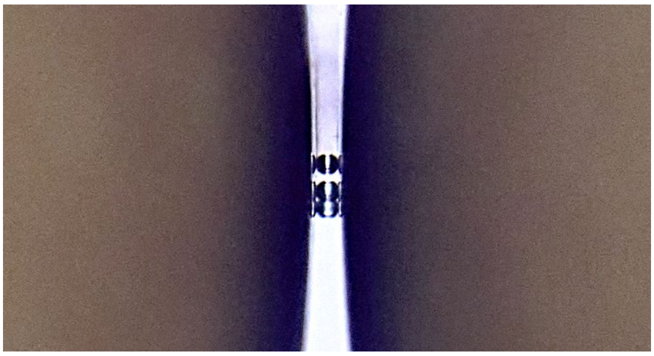

Fig. 2. Picture of gas bubbles between electrodes after breakdown, electrode distance 0.2 mm

## III. Statistical analysis

Breakdown of materials is a stochastic process. Therefore, statistical analysis must be performed to interpret the results. Because not all tests resulted in a breakdown, the Survival analysis method is used, with a 2-parameter Weibull distribution fit, as in (1):

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} e^{-x/\alpha^{\beta}} \quad (1)$$

In which the value of $x$ represents the value of the breakdown strength in $kV_{rms}/mm$ and $f(x)$ the corresponding probability. The scale parameter α indicates breakdown voltage at which 63.2% of all tests had a breakdown. The shape parameter β indicates the spread i.e. variation in test results. Higher values for β indicate lower variation. In this analysis the successful breakdowns are included as failure data points and the tests without breakdown are included as right censored data points, according to the Survival analysis methodology.

## IV. Results

Prior to the test procedure the synthetic ester liquid was tested with an electrode distance of 2.5 mm, according to the standard IEC 60156. This resulted in an average breakdown voltage of 85 $kV_{rms}$/2.5 mm. The permittivity was measured at 3.19 at a frequency range of 2 to 1000 Hz. Table 1 shows the Weibull parameters resulting from breakdown tests with varying electrode distance and frequency with all test results in $kV_{rms}/mm$.

Figure 3 graphs a, b and c show the breakdown strength $E_{BD}$ in $kV_{rms}/mm$ for each individual test in a Weibull probability plot. In each graph the frequency remains constant, and the electrode distance is varied per graph.

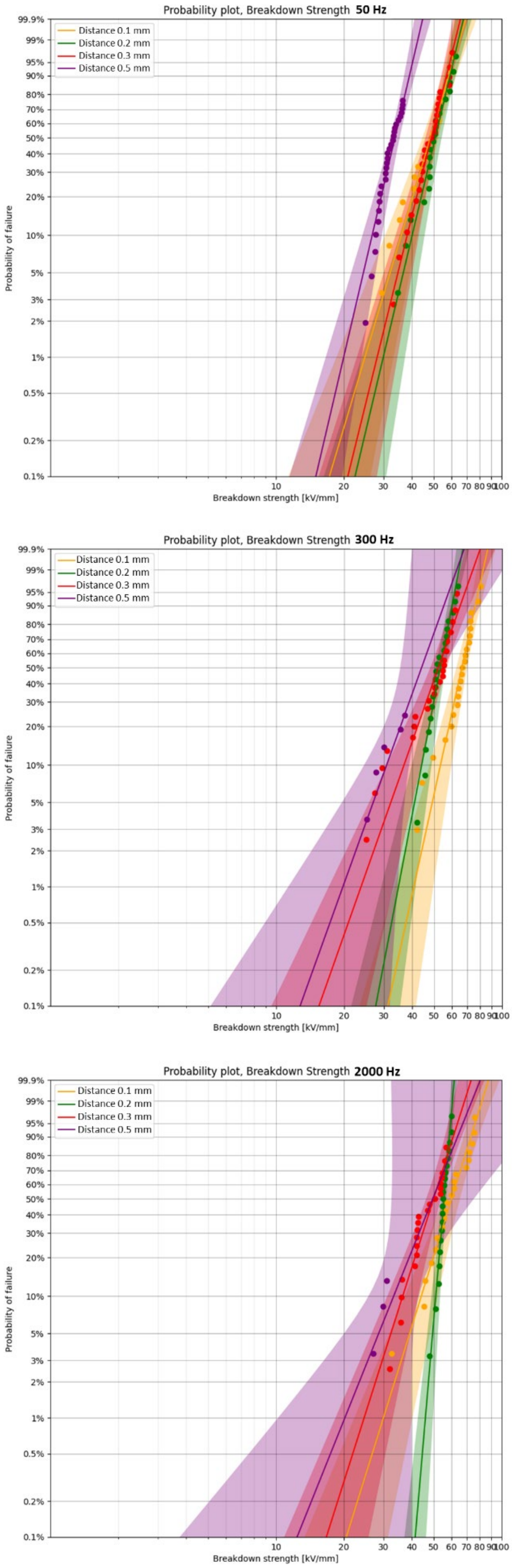


Fig. 3. 50 Hz (top), 300 Hz, (middle) and 2 kHz (bottom) test results Weibull probability plot of the scale paramater α in $kV_{rms}/mm$

Successful breakdown tests are shown as dots and the matching Weibull distribution is given as a straight line. The 95% confidence interval is given as a color shading.

TABLE I. BREAKDOWN TEST RESULTS*

| Frequency | 50 Hz | | 300 Hz | | 2 kHz | |
|---|---|---|---|---|---|---|
| Electrode Distance | α | β | α | β | α | β |
| 0.1 mm | 51,2 | 6.35 | 69.1 | 8.67 | 63.7 | 6.09 |
| 0.2 mm | 53.2 | 7.99 | 55.2 | 9.94 | 56.5 | 22.2 |
| 0.3 mm | 51.1 | 7.69 | 55.9 | 5.37 | 53.1 | 5.98 |
| 0.5 mm | 35.2 | 8.1 | 47.2 | 5.28 | 53.5 | 4.72 |

a. All values in $kV_{rms}/mm$

The first observation is that the scatter of the breakdown voltages is relatively high, except for 0.2 mm electrode distance at 2 kHz, see section V. Secondly it shows that the breakdown strength at 50 Hz is typically lower than the higher frequencies. Furthermore, the results show an (mainly) upward trend by decreasing electrode distance.

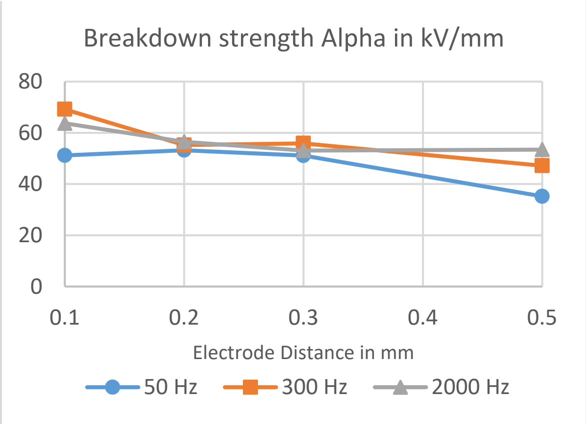


Fig. 4. Test results Weibull scale parameter α with breakdown strength of synthetic ester liquid

## V. DISCUSSION

It is a well-known fact that breakdown measurements in oil have a wide variation and reproducibility is limited see IEC 60156, [2] and [3]. The IEC standard prescribes 6 breakdown voltage measurements per test. However, IEC also recognizes that the reproducibility of individual measurements is +/- 30%. Therefore, the standard introduces an improved measurement taking 10 shots instead of 6 and removing the highest and lowest value, taking the average of the remaining 8 shots. This should increase the reproducibility. The results of these tests show that increasing the number of breakdown tests is required to increase reproducibility. Initial tests with only 6 samples showed too much scatter in the results. So, a total of 20 breakdown tests is used per setup. Using the Weibull analysis shows the scatter and enables the use of all samples without eliminating the lowest and highest breakdown values.

During this test sequence, it is observed that gas bubbles are hard to remove from the electrode surface. After stirring, cleaning the surface with a PE sheet, still minor gas bubbles showed to be present on the surface of the electrodes. Even during some breakdown tests, premature breakdown is observed, recognized by extremely low breakdown voltage and autonomous arc quenching prior to the protection operation. These breakdown test results are considered invalid and are not included in the test results. In such situations the test is repeated. It is a fair assumption that not all premature breakdowns due to invisible gas bubbles have been recognized. This contributes to the spread of test results. This is specifically valid for the test setup with small distances as used in this study. However, it should be considered as a potential contributing factor to the spread in results for the standardized 2.5 mm distance oil breakdown voltage tests as well. The breakdown mechanisms in liquids are not fully understood, however it is known that the breakdown strength of mineral oil reduces over time. The type of breakdown for synthetic ester needs to be considered. When assuming similar behavior as mineral oil, the timeframe of this test sequence using an AC voltage with a duration in the range of 5-15 seconds suggests two relevant types of breakdown mechanisms [4]:

1) Electronic breakdown according to the Percolation theory where due to high electric field, impurities and structural differences in the electrodes, high electric current densities occur. This causes local temperature increase and volumes of low density which propagate through the liquid through preferential paths (percolation). These preferential paths initiate the electric breakdown. Typically, the percolation theory is considered dominant in time frames in the millisecond to low second range with high electric field.

2) Fiber breakdown according to weak links caused by (fibrous) contaminants drifting towards the areas of high electrical field due to dielectrophoretic force. The contaminants disrupt / enhance the electric field at the tips of the particle and strongly reduce the breakdown strength. This theory is considered valid for stress times in the seconds to hours range and may result in much lower electric fields than observed with percolation theory.

During one of the test sequences in this study (at electrode distance of 0.2 mm) substantial lower breakdown voltages are observed triggering detailed inspections. It shows that accidentally fibrous particles (cleaning cloth) polluted the test liquid, after cleaning the test cell and replacing the liquid, the breakdown strength restores to regular results. These erroneous measurements results are considered invalid and not included in the study results. This could indicate that the relatively high breakdown strength in the range of 50 to 60 kV/mm measured during the successful test sequences for the smaller electrode distances are most likely related to the electronic breakdown mechanism according to the percolation theory.

At the electrode distance of 0.5 mm, specifically at 50 Hz, a lower breakdown strength is observed. Due to the higher voltages needed at this distance the total test duration increases. This provides more time for particles to drift towards the high electric field area and increases the likelihood of fiber breakdown. Additionally, a volume effect is valid for this electrode distance. Due to the wider distance a larger area is affected by the electric field also increasing the likelihood that fibers can drift in the area between the electrodes [5]. This combination of effects most likely explains a lower breakdown strength at larger electrode distances.

During the erroneous test cycle at 0.2 mm, it is also observed that at the frequency of 300 Hz and 2 kHz, the breakdown strength is less susceptible for fibers if they are carefully removed from the high electric field area than at 50 Hz. At 300 Hz and 2 kHz still high electric breakdown strength is observed with little scatter, explaining the higher β in the test results. At 50 Hz the average breakdown strength reduces by a factor 2 and is dropping in succeeding tests. This potentially indicates that particle drift is weaker at higher frequencies than 50 Hz. The dielectrophoretic force is depending on the conductivity- and permittivity differences between the particles and the surrounding medium, but also depends on the frequency. Note that the permittivity and conductivity also depend on frequency. This phenomenon is typically used in small particle separation at high frequencies. However, useful separation of larger particles is reported using the same principles [5]. It requires further study, but it is a valid assumption that the force $F_{DEP}$ acting on a particle is increasing with decrease of frequency. Note that the contribution of the difference in conductivity decreases with reducing frequency, see (2), and (3), with E the non-uniform electric field, $f_{CM}$ the Clausius-Mossotti factor, ε the permittivity, σ the conductivity and ω the angular frequency. In these formulas the subscripts p stands for particle and m for surrounding medium.

$$F_{DEP} \propto Re[f_{CM}]\nabla|E|^2 \qquad (2)$$

$$f_{CM} = \frac{\tilde{\varepsilon}_p - \tilde{\varepsilon}_m}{\tilde{\varepsilon}_p + 2\tilde{\varepsilon}_m} \; and \; \tilde{\varepsilon} = \varepsilon - i\frac{\sigma}{\omega} \qquad (3)$$

The experiments showed that the breakdown strength peaks typically at 300 Hz and reduces slightly at 2kHz, but the breakdown strength at both 300 Hz and 2 kHz are higher than at 50 Hz. The variations are larger at 50 Hz but are visible on all electrode distances. Note that at electrode distances of 0.2 and 0.3 mm no significant difference in average breakdown voltage is measured. It should also be noted that the displacement current through the sample at higher frequencies increases. The losses $P_\delta$ in the sample liquid increases with the frequency according to (4), with U the applied voltage, C the capacitance of the test cell and tan ($\delta$) the frequency dependent loss factor. At 50 Hz and 300 Hz the losses are low, however at 2 kHz the losses become more relevant. The tan(δ) was measured, as part of a related project, with a Novocontrol dielectric measurement system (to be published later), and it shows decreasing reduction of tan(δ) in the range of 1 kHz to 10 kHz. It is calculated that the losses at 2 kHz are appr. 2.7 times larger than at 50 Hz. It can be expected that the local temperature of the sample at high electric field increases, enhancing the percolation effect and reducing the breakdown strength.

$$P_\delta = U^2 \cdot \omega \cdot C \cdot \tan(\delta) \qquad (4)$$

These results are partly in line with literature where a decline of breakdown strength is predicted at higher frequencies, specifically for 1 kHz [4] and 5-9 kHz [6]. In [7] the breakdown strength of Midel 7131 with 50 ppm moisture vs. frequency at standard electrode distance of 2.5 mm is reported. The average breakdown strength reduces from appr. 17 kV/mm to appr. 15 kV/mm with very limited frequency dependency. It should be noted however that the test setup in this study differs significantly from the mentioned literature. Due to limitation in the power source the test frequency was limited to 2 kHz. Future work will study the frequency dependency of breakdown strength of synthetic ester liquids at a wider frequency range. This additional work is required to better understand the frequency dependency of breakdown strength with relation to the percolation theory.

## VI. Conclusions

In this work the effect of electrode distance and applied voltage frequency to synthetic ester liquid is studied. At all distances the breakdown strength is the highest at a frequency of 300 Hz and slightly reduced at 2 kHz. This behavior is different from solid materials e.g., PE and XLPE where experience and literature shows a steady decline in breakdown strength with increasing frequency. Although further study is required, it is believed that at higher frequencies the breakdown strength of synthetic ester liquid decreases further.

This study explains that new, degassed, and dried synthetic ester liquid can be successfully used for thin sample breakdown tests according to the standard IEC 60243 at frequencies of 300 Hz and 2 kHz because the breakdown strength of the liquid remains relatively stable as compared to the declining breakdown strength of PE and XLPE. A frequency dependent fiber breakdown mechanism is observed, where at 50 Hz the breakdown strength is strongly influenced by fibrous particles and at higher frequency this mechanism could be avoided by removing the particles from the area between the electrodes before the test.

## Acknoledgements

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