Study of Dielectric Behavior of Ester Transformer Liquids under ac Voltage

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ABSTRACT

As replacement of mineral oil, the application of ester liquids in large power transformers has become a hot topic in recent years. Understanding esters' dielectric behaviors under ac voltage is of vital importance for the insulation design of power transformers. This paper presents experimental studies on the ac dielectric strengths of synthetic ester and natural ester in quasi-uniform electric field, using mineral oil as a benchmark. The results show that esters have similar breakdown voltages to mineral oil when filtered and dehydrated. However, their breakdown voltages are significantly higher than mineral oil with the presence of particle and water contaminations. Furthermore, the breakdown voltages of esters are reduced more sharply than that of mineral oil with the increase of electrodes' Effective Stressed Area (ESA). Based on the experimental results, an estimation of the withstand voltages of transformer liquids in practical qualities was made when considering the particle effect, water effect and electrode area effect, and it was found that the 1-mm-gap withstand voltages of esters are higher than that of mineral oil.

Index Terms - **Power transformer, ac voltage, dielectric strength, insulating liquid,synthetic ester and natural ester.**

1 INTRODUCTION

MINERAL oil has been widely used in power transformers over a century. Its dielectric strength has been well-investigated and the resulting findings have been fully taken into account for the insulation design of power transformers. However, mineral oil is poor in biodegradability and could cause contamination to the environment. With increasing demand of environmentally friendly liquids from transformer industry, esters have been widely used in low and medium voltage distribution transformers [1]. The technical challenge we are facing is to extend the use of esters to power transformers with higher voltage ratings, where the conditions are more severe and the requirements for insulating liquids are much stricter.

With such a background, a significant amount of researches have been devoted to different aspects of esters performances [2-11]. The majority of these researches focused on ageing of materials [2, 3], fault diagnosis [4] and breakdown behavior of clean liquids/liquid-solid insulation systems [5-9]. Some [10, 11] focused on the pre-breakdown phenomena known as streamers of esters, using a needle to plane electrode configuration to provide a highly divergent field, which should be minimized during transformer design stage in order to reduce the possibility of partial discharge activity.

The uniform or quasi-uniform field configurations are often found in the insulation structure of power transformers, such as the oil gaps between windings or between windings and tank. In such configurations, the dielectric strengths of insulating liquids heavily depend on the liquid qualities; specifically the contaminations of water, solid particles and gas bubbles [12]. Therefore, to assist the insulation design or to check the liquid qualities, the breakdown voltages of insulating liquids are often tested using quasi-uniform configurations. Some standards, such as IEC 60156 and ASTM D1816, have specified the procedures of breakdown voltage test.

It has been reported that the breakdown voltages of clean esters and mineral oil are similar [13]. However, it is still unknown whether this statement is true or not when the liquids are contaminated. Since the physical and chemical properties of esters are different from mineral oil, their tolerance towards contaminations may differ, which can result in different breakdown strengths when contaminated. Based on previous researches, the dependence of the breakdown voltage of a transformer liquid on contaminations is summarized in the following sub-sections.

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1.1 PARTICLE CONTAMINATIONS

Insulating liquids can be contaminated by solid particles, the majority of which are cellulose particles and metallic particles [14]. For new transformers, the particles are mainly from the transformer manufacturing process or from the auxiliary components such as the pumps or coolers. When the transformer tanks are filled with insulating liquids, the liquids should be circulated and filtered for multiple passes in order to remove those particles.

Many efforts have been devoted to characterize the particle effect on dielectric strength of mineral oil, and it is widely accepted that the dielectric strength of mineral oil is significantly reduced by particles [15-17]. However, few studies have investigated the particle effects on the dielectric performance of esters.

1.2 MOISTURE CONTAMINATIONS

Moisture is unavoidable in in-service power transformers. It might ingress into a transformer from the atmosphere by poor working practices or through bad sealing, and moisture can also be produced during cellulose paper degradation. The presence of moisture in a transformer deteriorates transformer insulation by decreasing its dielectric strength and accelerating paper degradation, producing more moisture [18, 19].

Previous research concluded that the ac dielectric strengths of esters are higher than mineral oil over a wide range of absolute moisture content levels [20]. However, the particle content in liquid was not measured; hence it is unknown whether the differences are caused by moisture or the combination of moisture and particle contaminations in the transformer liquids. Therefore, the water effect on the breakdown voltages of clean liquid should be investigated.

In order to build up a relationship between the dielectric strengths of esters and the contamination levels, in this paper the breakdown strengths of two types of esters were studied under power frequency voltage (50 Hz ac) in quasi-uniform field, using mineral oil as the benchmark. The investigation includes four parts: (1) comparing the dielectric strengths of clean liquids; (2) studying the influence of particles contaminations (cellulose and copper); (3) the influence of water contamination and (4) the influence of electrode size on their breakdown voltages (BDV).

2 INSULATING LIQUIDS UNDER TEST

Two types of esters were investigated, namely a synthetic ester (Midel 7131 produced by M&I Materials) and a natural ester (Envirotemp FR3 produced by Cooper Power Systems). Midel 7131 is a type of pentaerythritol ester, with four '-COOR' parts synthesized to each side of the cross molecular structure. FR3 is a type of vegetable oil, fundamentally consisting of triglycerides and naturally esterified with three fatty acids. Due to the long chain molecular structure, esters commonly have higher density and higher viscosity than mineral oil. The higher viscosity reduces the convective heat transfer in a transformer and thus may require a more effective cooling system [2]. The permittivity, conductivity and water solubility of esters are also higher than mineral oil because of the polar and hygroscopic '-COO-' group.

In order to provide the benchmark for comparison with esters, a mineral oil (Nytro Gemini X produced by Nynas) was also studied under the same test conditions. The mineral oil mainly consists of hydrocarbon molecules, such as paraffins, naphthenes and aromatics.

The key properties of the three liquids under investigation are listed in table 1, as obtained from the Data Sheets provided by the oil manufacturers.

Table 1. Basic properties of Gemini X, Midel 7131 and FR3.

Properties	Unit	Gemini X	Midel 7131	FR3
Density @ 20 °C	g/cm^3	0.895	0.97	0.92
Viscosity @ 40 °C	mm^2/s	12	28	34
Viscosity @ 100 °C	mm^2/s	2.4	5.3	8.0
Pour point	°C	-40	-60	-20
Flashpoint	°C	135	275	320
Acidity	mg KOH/g	0.01	<0.03	0.02
Water solubility @ 20 °C	ppm	55	2700	1100
Relative permittivity@ 25°C		2.2	3.2	3.2
Volume resistivity@ 25 °C	Ω/cm	51×10^{12}	12×10^{12}	20×10^{12}
Dissipation factor @ 90 °C		< 0.001	< 0.03	<0.03

3 CONTAMINATION EFFECT ON BDV

3.1 EXPERIMENTAL DESCRIPTION

3.1.1 SAMPLE PREPARATION

To obtain clean liquid samples, the new insulating liquids were firstly filtered through a membrane filter unit with pore size of 0.2 μm for three cycles. Then, the purified samples were dehydrated and degassed in a vacuum oven at less than 5 mbar and 80° C for 48 h. After that, a further 24 h were given for the samples to cool down to ambient temperature under vacuum condition. The processed samples were then stored in sealed glass containers and ready for use. The well-processed liquids through the above procedure are called "clean" samples.

When investigating the influence of particles on breakdown strength, clean samples were artificially contaminated by adding cellulose and copper particles. Before being added, the particle contaminants were dried for 10 h or more in an air-circulating vacuum oven at 80° C. The contaminated samples were blended into the liquid by magnetic stirrer for at least 15 minutes to ensure even distribution of particles in liquids. As an example, Table 2 gives the typical size distributions of cellulose and copper particles after sample preparation, where the sum of all particles with diameters larger than 5 μm is defined as particle content of the liquid [14].

Table 2. Distributions of cellulose and copper particles number with size in 100 ml testing samples.

Size (μm)	1-5	5-15	15-25	25-50	50-100	100-200	>200
Cellulose	16536	6706	1163	286	26	0	0
Copper	29490	15480	3590	3300	720	10	0

When studying the moisture effect on breakdown strength, the clean samples were humidified using the equilibrium method proposed in [21], i.e. placing the dry samples in clean glass dishes at a desiccator, within which the relative humidity of the air is controlled by a mixture of glycerine and water. The glass dishes were used to provide large surface areas to speed up the moisture equilibrium between the samples and wet air. At least two weeks were given for the equilibrium process before the samples were collected and sealed in a clean glass container.

The qualities of the samples were checked prior to the experiments. The particle content was measured by a HIAC automatic particle counting system, and the water content by standard Karl Fischer titration method.

For clean samples, the particle contents (>5 μm per 100 ml) were less than 500, and the relative water content were approximately ranged from 3 to 5% RH.

3.1.2 TEST METHOD

The breakdown voltages of testing samples were measured at ambient temperature according to ASTM D1816 specification using a Baur75 automatic tester. The VDE electrodes were used in the tests. The electrodes consist of two spherical electrodes of 36 mm in diameter, facing each other with a gap of 1 mm, while the details are explained in Section 4.2. The VDE electrodes were chosen because they are more sensitive to oil qualities than spherical electrodes as specified in IEC 60156 [22]. The volume of the test container was approximately 400 ml.

In the experiments, the applied voltage was increased continuously from 0 kV at a rate of 0.5 kV/s until a breakdown occurred. To avoid excessive degradation of the liquid, the applied voltage is tripped by a current relay when the breakdown current exceeds 4 mA. For mineral oil, the time interval between two successive breakdowns was set at 1 minute [23], during which a magnetic stir worked for the expulsion of breakdown by-products. For esters, at least 5 minutes was given between two successive breakdowns [24], because esters have higher viscosities than mineral oil and thus the expulsion of the breakdown by-products is slower. When testing the samples with particles, the magnetic stir ensured the even distribution of particles in the oil gap and avoids the particles depositing at the bottom of the test container.

The average BDVs of testing liquids were determined based on 40 measurements, which also gave the probability distributions of the breakdown voltage.

3.2 EXPERIMENT RESULTS

3.2.1 BREAKDOWN VOLTAGE DISTRIBUTION

Figure 1 shows the average breakdown voltages and standard deviations of mineral oil and esters. For well-processed samples, Gemini X has an average BDV of 47.7 kV, higher than 45.1 kV for Midel 7131 of and 44.5 kV for FR3, with a standard deviation of 4.1 kV, lower than 4.5 kV for Midel 7131 and 4.3 kV for FR3. Compared to our previous results reported in [13] using the same test configuration but samples without processing, the average BDV for all liquids are increased and the standard deviations for all liquids are reduced. This is attributed to the removal of water and particles from the samples. One interesting observation from this comparison is that, the BDV of Gemini X is increased to the most extent in all the liquids, promoting Gemini X from the lowest ranking for unprocessed liquids to the highest ranking for well-processed liquids.

The measurement results also confirm that the BDV of esters follow Weibull distribution, similar to that of mineral oil as reported in [6].

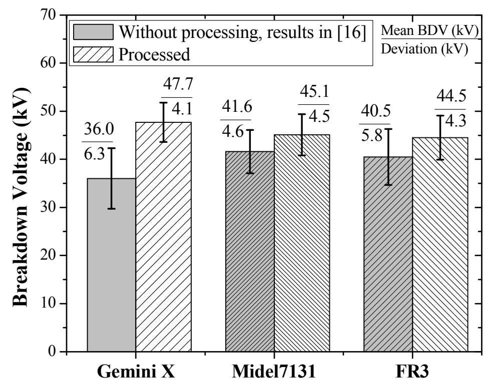

Figure 1. Breakdown voltages and standard deviations of Gemini X, Midel 7131 and FR3 (Error bars indicate standard deviations).

Figure 2 shows the Weibull distributions of breakdown voltages of Gemini X, Midel 7131 and FR3. In spite of the slight deviation at high (>95%) and low (<5%) probability ranges, the measurement results and the expected Weibull distribution are overlapped well in the range between 5% - 95% for all three liquids, which indicates that the BDV of both mineral oil and esters adhere to the Weibull distribution.

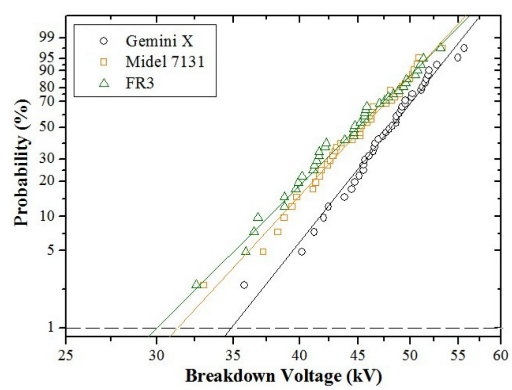

Figure 2. Weibull distribution of breakdown voltages of Gemini X, Midel 7131 and FR3 (Points are breakdown voltage results, and solid lines are expected Weibull distributions).

Existing international standards have already specified the BDV requirement for new insulating liquids used in power transformers [24-26]. The average BDV of unused mineral oil, synthetic ester and natural ester should exceed 70 kV/2.5 mm, 50 kV/2.5 mm and 30 kV/mm for transformers with nominal voltages higher than 234 kV, respectively. The results obtained above indicate, when being clean, all the liquids could meet the requirement.

In the insulation design of power transformers, the withstand voltage are more commonly used than the average breakdown voltage. The withstand voltage is considered as the level where the risk of failure is acceptably low, usually with a probability of 1% [27]. The withstand voltage of both mineral oil and esters can be predicted from the fitted Weibull distribution of breakdown voltages. However, the prediction always comes with an inevitable uncertainty; therefore the 95% confidence interval of the prediction should be evaluated.

Table 3 shows the prediction results of the withstand voltage and the 95% confidence interval for both mineral oil and esters. For the well processed samples, it is seen that the withstand voltages of Midel 7131 and FR3 are slightly lower than that of Gemini X. Considering the width of the confidence intervals, it might be more reliable to use the lower limit of the interval than the withstand voltage for the insulation design.

Table 3. Prediction of withstand voltages using Weibull distribution.

	Gemini X	Midel 7131	FR3
Withstand voltage $U_{1\%}$ (kV)	34.6	31.4	30.2
95% confidence interval (kV)	[32.1, 37.8]	[30.2, 34.9]	[27.6, 33.5]

3.2.2 PARTICLE EFFECT ON BDV

Figure 3 plots the average breakdown voltages and standard deviations of mineral oil and esters contaminated by cellulose particles. The shaded areas from light to dark represent the contamination levels as specified in [14]. For Gemini X, when the particle content reaches 20,000, the breakdown voltage drops to 50% of that of the clean oil, which conforms well to the previously published results in [19]. Furthermore, the breakdown voltage of Gemini X seems more sensitive to the cellulose particles than Midel 7131 and FR3. For clean samples, the breakdown voltage of Gemini X is higher than Midel 7131 and FR3, however, it drops quickly and is only 80% of the breakdown voltages of FR3 when the particle content increases to 20,000.

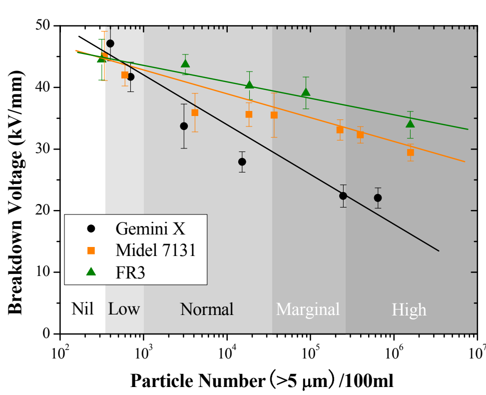

Figure 3. Breakdown voltages and standard deviations of Gemini X, Midel 7131 and FR3 contaminated by cellulose particles (The shaded areas from nil to high represent the contamination levels).

Figure 4 plots the average breakdown voltages and standard deviations of mineral oil and esters contaminated by copper particles. Similar to cellulose particles, the breakdown voltage of Gemini X reduces more remarkably with the increase of copper particle content than Midel 7131 and FR3. When the copper particle content reaches 3,000, the breakdown voltage of Gemini X is reduced to 40% of the clean sample, in contrast to 70% for Midel 7131 and 73% for FR3.

Although metallic particles exist in small quantity in in-service transformer liquids [14], they can reduce the breakdown voltages much more significantly than cellulose particles at a given content. For example, when the copper particle content is 2,000, the breakdown voltages are 26.1 kV, 33.4 kV and 35.7 kV for Gemini X, Midel 7131 and FR3 respectively; whereas the breakdown voltages are 39.1 kV, 41.6 kV and 42.7 kV for Gemi ni X, Midel 7131 and FR3 with 2,000 cellulose particles.

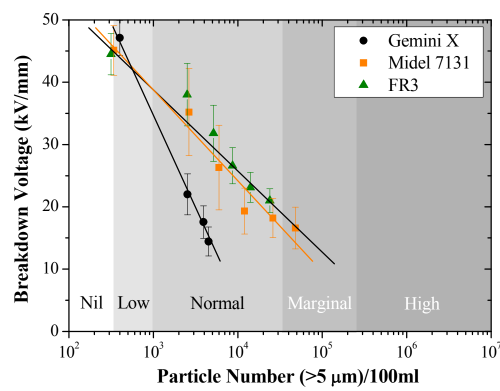

Figure 4. Breakdown voltages and standard deviations of Gemini X, Midel 7131 and FR3 contaminated by copper particles (The shaded areas from nil to high represent the contamination levels).

For the purpose of supervision and maintenance of transformer liquids, existing international standards [24, 28, 29] have specified the BDV criterion of mineral oil, synthetic ester and natural ester, which are 50 kV/2.5 mm, 45 kV/2.5 mm and 50 kV/2 mm for transformers with nominal voltages higher than 234 kV, respectively. For in-service transformers which are mainly contaminated by cellulose particles, 130,000 is recommended to classify the particle contamination levels between marginal and high for mineral oil encountered in an in-service transformer [14]. In Figure 3, this particle content corresponds to a BDV of 22.5 kV/mm for Gemini X, which is in good agreement with the BDV criterion specified for mineral oil.

The classification of contamination levels based on mineral oil is not suitable for esters, because the particle effects on the breakdown voltages are different between mineral oil and esters. For example, the BDV criterion for Midel 7131, 45 kV/2.5 mm, correspond to a particle content of 10,000,000, and the BDV criterion for FR3, 50 kV/2 mm, correspond to a particle content even higher.

The results show that in the presence of cellulose or metallic particles, the breakdown performances of esters are relatively superior to mineral oil, indicating that they might be able to maintain good dielectric strengths even being contaminated during transformer operation. The difference of particle effect between mineral oil and esters can be attributed to their viscosities. It is found that a charged metallic particle moves faster and travels further in mineral oil than in esters [30] and leads to smaller breakdown voltages. Reference [31] hypothesized that the reduction of viscosity might result in the 'loosening up' of the liquid molecules, which favors the mobility of charge carriers and thus makes breakdown more easily in an insulating liquid. The test results in Figures 3 and 4 can be used to calculate the parameters listed in table 4, using the relationship between the BDV and the particle contents as shown in equation (1) [32],

$$BDV(N) = a \cdot \ln(N \cdot d) + b = a'\ln(N) + b' \tag{1}$$

where N is the particle content, d is the maximum particle diameter, and a' and b' are constants depending on the particle material and the liquid type,

Table 4. Parameters used in the particle effect on liquid breakdown voltages.

Particle	Parameter	Gemini X	Midel 7131	FR3
Viscosity η (Cst)		12	28	32
Cellulose	b'	62.91	52.60	53.22
	a' $(-90/\eta)$	-7.45 (-7.50)	-3.71 (-3.22)	-2.98 (-2.82)
Copper	b'	133.87	78.12	76.72
	a' $(-400/\eta)$	-32.60 (-33.33)	-13.55 (-14.29)	-12.96 (-12.50)

The results clearly show that parameter a' is inversely proportional to the viscosity of liquid. Therefore, the relationship between the BDV and the particle contents of a transformer liquid can be rewritten as equation (2),

$$BDV(N) = -\frac{K}{\eta} \cdot \ln(N) + b' \tag{2}$$

where N is the particle content, η is the viscosity of liquid, K is a constant value determined by the particle material (for cellulose K=90 and for copper K=900) and b' is a constant value determined by the liquid type.

3.2.3 MOISTURE EFFECT ON BDV

Figure 5 plots the average breakdown voltages and the standard deviations of mineral oil and esters versus the absolute water content in ppm. The breakdown voltage of dry Gemini X is slightly higher than dry Midel 7131 and FR3, but it drops steeply when the moisture is increased. Similar test results were also documented in [5, 20]. However, the comparison based only on absolute water content is not sufficient. Since the water saturation level of Gemini X is much smaller than those of Midel 7131 and FR3, the absolute water content cannot effectively indicate the water state (dissolved or free) in the liquid. It is therefore more reasonable to compare their breakdown voltages using relative water content.

Figure 6 plots the average breakdown voltages and the standard deviations of mineral oil and esters versus their relative water contents. In terms of the relative water content, the water effects of mineral oil are similar to esters. The breakdown voltages of the clean samples are not significantly affected by moisture level up to 20% RH. Above 20% RH, their breakdown voltages are gradually reduced with the increase of the relative water contents. At 70% RH, the breakdown voltage of Gemini X decreases to 20 kV/mm, while the breakdown voltages of Midel 7131 and FR3 are reduced to 10 kV/mm. When the relative water content is further increased, their breakdown voltages are gradually stabilized to an extreme low level due to water saturation.

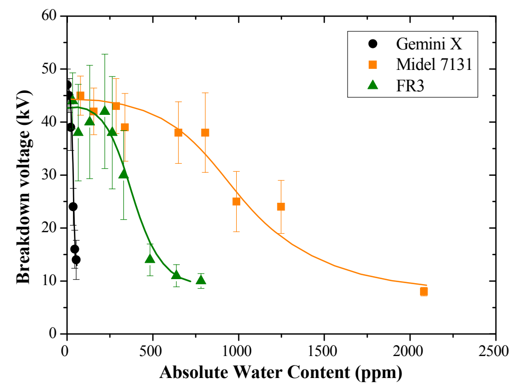

Figure 5. Breakdown voltages and standard deviations of Gemini X, Midel 7131 and FR3 versus absolute water content (Error bars are standard deviations).

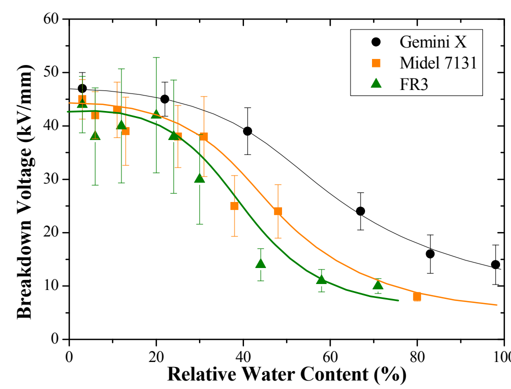

Figure 6. Breakdown voltages and standard deviations of Gemini X, Midel 7131 and FR3 versus relative water content (Error bars are standard deviations).

In clean transformer liquids, the water exists in two states, namely the associated water (dissolved water) and the dissociated water (free water) [33]. At low relative water content, most of the water exists as associated water. The mobility of the associated water is low since the water molecules are combined with the polar parts of hydrocarbon molecules by weak H-H bonds [34]. The associated water might be further restricted when the water molecules act as intermolecular bridges and connect two or more molecules together [34]. Therefore, the breakdown voltages of transformer liquids are relatively high due to the lack of mobile water molecules which can be easily ionized to charge carriers.

When the relative water content is high, some water might exist as free water. These free water molecules function as the charge carriers and reduce the breakdown voltage of transformer liquids. Therefore, the conductivities of insulating liquids with high water contents are usually increased [33] and their breakdown voltages are reduced with the increasing of relative water content.

3.2.4 COMBINED EFFECT OF PARTICLE AND MOISTURE ON BDV

For contaminated transformer liquids, water will affect their breakdown voltages more significantly [19]. Figure 7 shows the water effect on the breakdown voltages of transformer liquids contaminated by cellulose particles at a particle content of 25,000. Comparison of Figures 6 and 7 shows that, the breakdown voltage of contaminated Gemini X drops significantly when combined with water, especially at very dry state, a small variation of the relative water content would lead to a significant reduction of the breakdown voltage. However, the breakdown voltages of contaminated Midel 7131 and FR3 behave similar to those of clean liquids. At low moisture level up to 15% RH, the breakdown voltages of contaminated Midel 7131 and FR3 are not affected, which conforms to previous results reported in [20].

References [19] and [35] explained that most of the water in mineral oil is absorbed by the hygroscopic particles, and the wet particles might function as charge carriers, thus reducing the breakdown voltage of mineral oil. However, esters are much more hygroscopic than mineral oil. In esters, a large amount of water might be absorbed by esters instead of particles, reducing the number of charge carriers. Therefore, the breakdown voltages of esters are less dependent on water than mineral oil in the presence of particles.

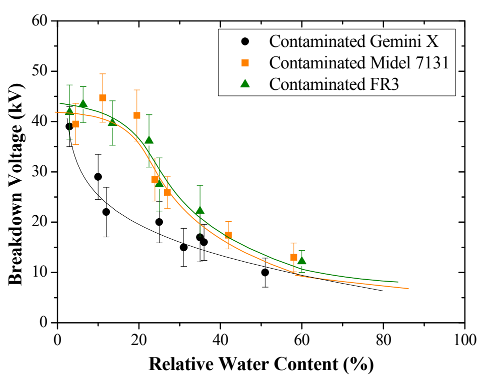

Figure 7. Breakdown voltages and standard deviations of contaminated transformer liquids versus relative water content (Error bars are standard deviations).

4 ELECTRODE AREA EFFECT ON BDV

It is well known that the breakdown strength decreases with both the increase of electrode area and gap distance between electrodes. Overall, the area and distance effect is known as scale effect or volume effect which needs to be considered in the insulation design of power transformers [36]. The breakdown voltage of transformer liquid under uniform/quasi-uniform field in the full scale of transformer is usually estimated by extrapolation from small scale tests following the parallel/series breakdown probability models.

Although the area effect of mineral oil has been well-established in [36-38], it is still unknown whether esters have the same trend as mineral oil when electrode area is enlarged. Therefore, the electrode area effect on the breakdown voltages of esters is investigated here.

4.1 THEORETICAL ANALYSIS

The Weibull distribution is employed to perform the statistical analysis of the area effect for esters. Using the weakest-link theory and the parallel breakdown probability model [39], the area effect on breakdown voltages of transformer liquid can be expressed by equation (3),

$$\begin{cases} \log(\alpha) = a - b \times \log(S) \\ \beta = \dfrac{1}{b} = \text{constant} \end{cases} \tag{3}$$

where α is the scale parameter, β is the shape parameter, a, b are constants determined by the transformer liquid. S is the Effective Stressed Areas (ESA) of electrode, which is defined as the electrode area which is stressed under an electric field larger than 90% of the maximum electric field; because the breakdown strength of insulating liquid is closely related to the ESA rather than the total electrode area [39]. Detailed derivation is described in the Appendix.

The following three technical points can be derived based on this equation: (1) there is a linear relationship between the logarithmic scale parameter α and the logarithmic ESA of electrode; (2) if parallel breakdown probability model is ideally followed, the shape parameter β of the Weibull plot is independent of the ESA of the electrode; (3) the reduction rate b of scale parameter α is inversely proportional with the shape parameter β.

4.2 EXPERIMENTAL DESCRIPTION

Figure 8 shows seven types of electrodes employed for the breakdown voltage tests, including a sphere electrode, a VDE electrode, and 5 types of round flat electrodes. The sphere and VDE electrodes are with small electrode areas. The edges of the flat electrodes are curved with a radius of 1 mm. All the electrodes are made from copper, and their surfaces are carefully polished prior to experiments. Table 5 lists the electrodes diameters and corresponding ESA.

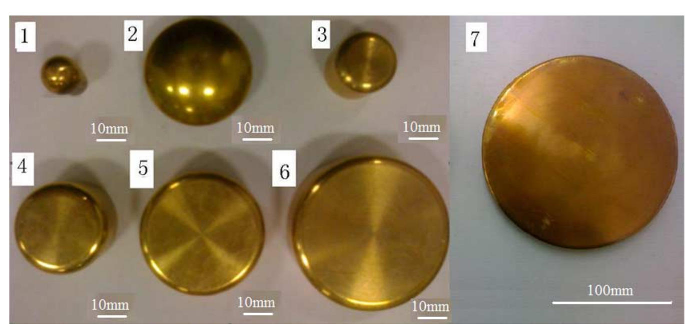

Figure 8. Electrode configurations for breakdown voltage measurement, (1) sphere electrode, diameter =12.5 mm, (2) VDE electrode, diameter =36 mm, (3)-(7) flat electrode, diameter =20 mm, 30 mm, 40 mm, 50 mm, 150 mm.

Table 5. Diameters and ESA of electrodes for breakdown voltage measurements.

Number	1	2	3	4	5	6	7
Diameter (mm)	12.5	36	20	30	40	50	150
ESA (mm^2)	2.17	5.12	283	660	1194	1885	17671

The clean samples were used in the experiments. For electrodes 1 to 6, the breakdown voltages were measured using the Baur75 tester as described in Section 3.1. The gap distance was set at 1 mm. For electrode 7, since the electrode is too large to fit into the Baur75 tester, the breakdown voltage was measured using the setup shown in Figure 9. The voltage was provided by a single phase transformer up to 70 kV. A 500 kΩ resistor was connected between the high voltage supply and the test object to limit the current when a breakdown occurred. No more than 20 breakdowns were done on one liquid sample to reduce the influence of deteriorations of liquid caused by breakdown energy. The time interval between two breakdowns was increased to 15 minutes to give sufficient time for dispersion of the gaseous products.

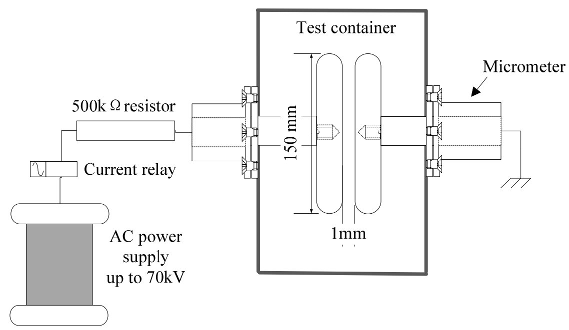

Figure 9. Test setup of breakdown voltage measurement for electrode 7 (flat electrode, diameter =150 mm).

4.3 EXPERIMENTAL RESULTS

Figure 10 shows the Weibull plots of ac breakdown voltages for Gemini X, Midel 7131 and FR3. In spite of slight scattering, Weibull distribution can still be applied to fit the probability of breakdown voltages for both mineral oil and esters. It is also noticed that the slopes of Weibull plots of Gemini X are similar among all electrodes, but those of esters are significantly different. For Midel 7131, the slopes for electrode 1 and electrode 2, electrode 6 and electrode 7, are so different that their Weibull plots are crossed.

Table 6 lists the scale parameter α and shape parameter β estimated from the Weibull plots for all experiment conditions. It is seen that the scale parameter, α, is decreased from 52.4 kV, 49.1 kV and 49.3 kV of the sphere electrode (electrode 1) to 31.8 kV, 25.7 kV and 27.5 kV of the flat electrode (electrode 7) for Gemini X, Midel 7131 and FR3, respectively. This reduction clearly shows the electrode area effect on the breakdown voltage of transformer liquids.

On the other hand, the shape parameter, β, of each individual liquid varies with different experiment conditions but stays within a range. Table 7 lists the average values and standard deviations of the shape parameters β calculated from the test results of Gemini X, Midel 7131 and FR3. It is clearly seen that the shape parameter of Gemini X is larger than those of Midel 7131 and FR3. In other words, the scattering of the breakdown voltage for Gemini X is smaller than those of Midel 7131 and FR3.

Since the electrode area effect is indicated by the reduction of the scale parameter α with increasing ESA, the relationship between the scale parameter α and ESA is plotted, as shown in Figure 11. The solid lines are the linear fittings of the scale parameter by the least square method.

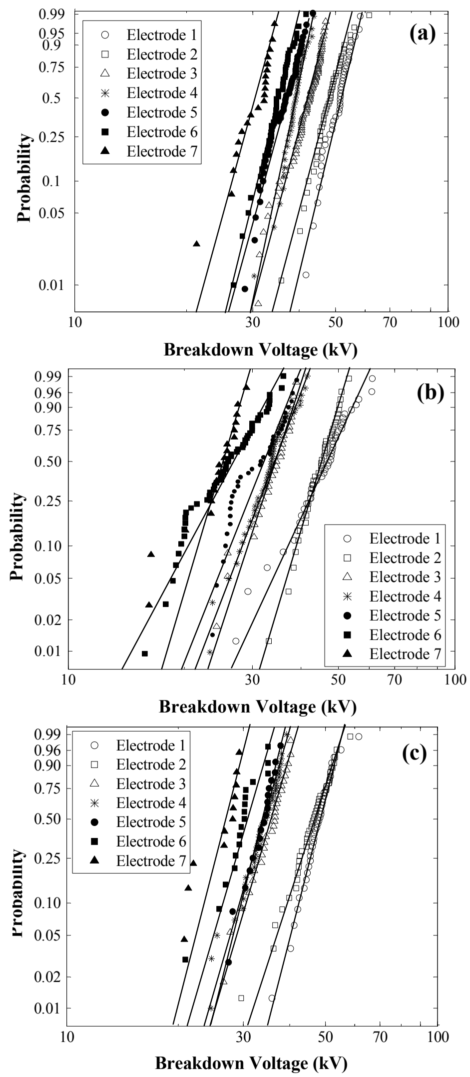

Figure 10. Weibull plots of ac breakdown voltages for Gemini X, Midel 7131 and FR3, (a) Gemini X, (b) Midel 7131, (c) FR3.

Table 6. Weibull Scale Parameter α and Shape Parameter β Estimated from Weibull Plots for Gemini X, Midel 7131 and FR3

Electrode	Gemini X		Midel 7131		FR3	
	α	β	α	β	α	β
1	52.4	15.2	49.1	7.19	49.3	12.9
2	50.3	13.7	47.4	10.4	49.1	10.6
3	43.6	14.4	35.0	9.22	36.9	13.0
4	40.0	17.9	35.6	12.1	35.3	13.0
5	38.1	12.6	33.1	7.72	34.8	15.6
6	36.3	13.5	28.1	6.02	31.3	10.2
7	31.8	12.5	25.7	10.0	27.5	12.2

Table 7. Average value and standard deviation of the shape parameters β calculated from the test results for Gemini X, Midel 7131 and FR3

Liquids	Average β	Standard deviation	90% confidence interval
Gemini X	14.3	1.9	[11.2, 17.3]
Midel 7131	9.0	2.1	[5.5, 12.4]
FR3	12.5	1.8	[9.5, 15.5]

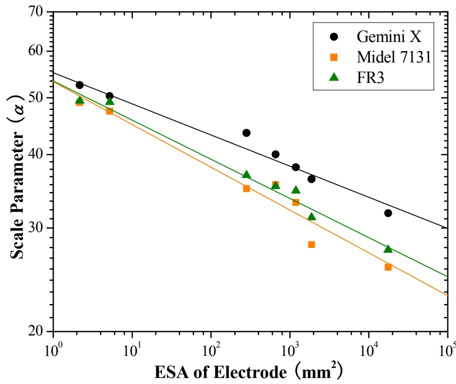

Figure 11. Scale parameter α of Weibull plots versus ESA of electrodes for Gemini X, Midel 7131 and FR3, (a) Gemini X, (b) Midel 7131, (c) FR3.

It can be seen that the scale parameters of Midel 7131 and FR3 reduce more sharply than Gemini X with the increase of ESA of electrode. The reduction rates of logarithmic of scale parameter *α,* in Figure 11 are 0.054, 0.067 and 0.073 for Gemini X, Midel 7131 and FR3, respectively and they are roughly inversely proportional to the shape parameter *β*.

Table 8 lists the parameters of *a* and *b* of the three liquids used in equation (3). Using the shape parameters listed in table 8, the Weibull distribution of breakdown voltages are expressed in equation (4) for Gemini X, Midel 7131 and FR3, respectively, where *P* is the breakdown probability of a transformer liquid, *S* is the ESA of electrode in the unit of mm^2, and *E* is the electric field in the liquid gap in the unit of *kV/mm*.

Table 8. Parameters of *a* and *b* used in area effect equations for Gemini X, Midel 7131 and FR3.

Liquids	*a*	*b*
Gemini X	1.7391±0.0096	0.0508±0.0034
Midel 7131	1.7195±0.0140	0.0697±0.0056
FR3	7.7274±0.0140	0.0666±0.0055

$$\begin{cases} P_{\mathrm{GeminiX}}(E)=1-\exp\left(-S^{0.73}\left(E/54.8\right)^{14.3}\right) \\ P_{\mathrm{MIDEL7131}}(E)=1-\exp\left(-S^{0.63}\left(E/52.4\right)^{9.0}\right) \\ P_{\mathrm{FR3}}(E)=1-\exp\left(-S^{0.83}\left(E/53.4\right)^{12.5}\right) \end{cases} \quad (4)$$

5 APPLICATION OF ESTERS IN LARGE POWER TRANSFORMERS

Although small scale tests of well-processed mineral oil and esters give similar dielectric strengths, the results in this paper indicate that their behaviors are quite different under the conditions when the insulating liquids are used in large volumes and in practical qualities. Therefore, all the influences should be taken into consideration during the insulation design. Estimation of the withstand strength of a transformer liquid for practical use can be achieved by several stages.

Firstly, the breakdown voltage distribution of a well-processed liquid obtained in this study should be extrapolated for electrode with realistic surface area, secondly its withstand voltage is calculated. Then, the liquid qualities as in in-service transformers should be considered finally, in terms of particle effect and water effect, to derive the withstand voltage of the transformer liquid.

Assume the electrode has an effective stressed area of 1 m^2, an example in table 9 is provided to calculate the withstand voltage with 1% failure probability, which can be obtained using equation (4). When considering the cellulose particle content of 25,000 and water contaminations of 5% RH as typical values encountered in a in-service transformer, the reduction factors can be obtained from Figures 3 and 7, so that the withstand voltage can be calculated as given in table 9.

Table 9. Estimation of 1% withstand voltage (kV/mm) for Gemini X, Midel 7131 and FR3 of In-Service Qualities.

Quality	Gemini X	Midel7131	FR3
'clean'	19.1 kV	11.7 kV	13.9 kV
'practical quality'	8.1 kV	9.3 kV	12.1 kV

The results shows that the withstand strengths of transformer liquids in practical scale and qualities are much smaller (only about 1/4) than the breakdown voltages derived from small scale tests using clean liquids. The withstand strengths of Midel 7131 and FR3 in in-service condition are expected to be slightly higher than Gemini X.

6 CONCLUSIONS

In this paper, the breakdown voltages of clean mineral oil and esters were studied under ac voltage using small scale tests following standard procedure. Although the average BDV of clean Gemini X is slightly higher than clean esters, they can be regarded as similar when considering the safety margins used in transformer insulation design.

However, the dielectric strengths of insulating liquids perform differently when practical situations are considered. First, in the presence of particles, although the dielectric strengths of esters are reduced, they reduce significantly less than mineral oil, probably due to higher viscosities. Second, in terms of relative water content, the dielectric strengths of clean liquids are not significantly affected up to 20% RH. For relatively contaminated liquids, the dielectric strength of mineral oil is reduced significantly as soon as water exists in mineral oil, whereas esters are almost not affected by water content up to 15% RH. Thirdly, esters are more sensitive to electrode area effect than mineral oil, and their dielectric strengths are decreased more sharply when increasing the effective stressed area of electrode.

Since the ac withstand voltage of a transformer liquid is of vital importance to the insulation design, these differences between mineral oil and esters should be taken into consideration when designing an ester-filled transformer, or retro-filling existing power transformers.

This paper also provides an estimation method for calculating the withstand voltages of insulating liquids in practical conditions, by considering the particle effect, water effect and electrode area effect.

APPENDIX

As shown in Section 3.2, Weibull distribution can be employed to fit the breakdown voltage distribution of transformer liquids. In this part, the derivation of area effect using Weibull distribution is described.

It is generally accepted that the breakdowns of transformer liquids in uniform ac fields are caused by the 'weakest-links', existing both in the bulk oil or on the surface of the electrodes [38]. With the enlargement of the electrode area, the number of 'weakest-links' will increase proportionally. Following the parallel breakdown probability model [40], an electrode with ESA of S (Figure 12a) can be regarded as n pieces of basic element S_0 connected in parallel (Figure 12b).

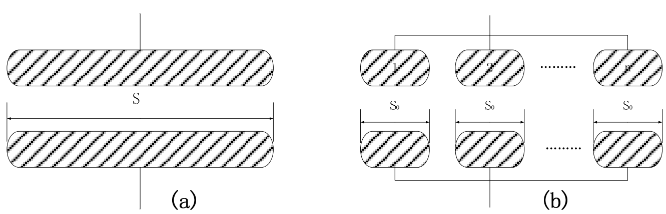

Figure 12. The parallel breakdown probability model used for electrode area effect.

The breakdown voltage distributions of the electrode S and the basic element S_0 should follow Weibull distribution as expressed in equations (5) and (6), where $P(E)$ is the failure rate of the test liquid at a electric field of E, α is the scale parameter (shows the breakdown voltage at a failure probability of 63%) and β is the shape parameter (shows the scattering of the breakdown voltage).

$$P(E) = 1 - e^{-(\frac{E}{\alpha})^{\beta}} \tag{5}$$

$$P_i(E) = 1 - e^{-(\frac{E}{\alpha_i})^{\beta_i}} \tag{6}$$

Since the elements are connected in parallel, the relation between the breakdown probability P and P_i can be expressed by

$$1 - P = \prod_{i}^{n} (1 - P_i) \tag{7}$$

$$\ln(1 - P) = \sum_{i}^{n} \ln(1 - P_i) \tag{8}$$

Equation (8) can be rearranged as

$$(\frac{E}{\alpha})^{\beta} = \sum_{i}^{n} (\frac{E}{\alpha_i})^{\beta_i} = \frac{S}{S_0} (\frac{E}{\alpha_i})^{\beta_i} \tag{9}$$

Solving equation (9), we obtain the following two equations expressed as

$$\beta = \beta_i \tag{10}$$

$$\alpha = \alpha_i \left(\frac{S}{S_0} \right)^{-\frac{1}{\beta}} \tag{11}$$

Equation (10) indicates that the shape parameter β of the Weibull distribution is independent of the ESA of the electrode. Thus, it is a constant determined by the liquid type. Equation (11) can be further expressed as

$$\log(\alpha) = -\frac{1}{\beta_i} \log(S) + \left(\frac{1}{\beta_i} \log(S_0) + \log(\alpha_i) \right) \tag{12}$$

Since the S_0, α_i and β_i can be regarded as constants, Equation (12) can be written as equations (13) and (14), where α, β are scale and shape parameters of the Weibull distribution of electrode S, and a, b are constants determined by the type of liquid. It is clear that b is reciprocal of the shape parameter β.

$$\log(\alpha) = a - b \times \log(S) \tag{13}$$

$$\beta = \frac{1}{b} = \text{constant} \tag{14}$$

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REFERENCES

[1] Z.D. Wang, A. Darwin, and R. Martin, "New insulation fluids: use of environmentally friendly fluids in power transformers", CIGRE Colloq., Bruges, Belgium, pp. PS1-04, 2007.

[2] 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.

[3] 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.

[4] I. Khan, Z.D. Wang, and I. Cotton, "Dissolved gas analysis of alternative fluids for power transformers", IEEE Electr. Insul. Mag., Vol. 23, pp. 5-14, 2007.

[5] H. Borsi, "Dielectric behavior of silicone and ester fluids for use in distribution transformers", IEEE Trans. Electr. Insul., Vol. 26, pp. 755-762, 1991.

[6] D. Martin and Z.D. Wang, "Statistical analysis of the ac breakdown voltages of ester based transformer oils", IEEE Trans. Dielectr. Electr. Insul., Vol. 15, pp. 1044-1050, 2008.

[7] K. J. Rapp, C. P. McShane, J. Vandermaar, D. Vukovic, and S. Tenbohlen, "Long gap breakdown of natural ester fluid", Int'l. Conf. High Voltage Eng. Applicat. (ICHVE), New Orleans, USA, pp. 104-107, 2010.

[8] 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.

[9] 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.
[10] 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.
[11] 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, 2010.
[12] M. G. Danikas, "Breakdown of transformer oil", IEEE Electr. Insul. Mag., Vol. 6, No. 5, pp. 27-34, 1990.
[13] X. Wang and Z.D. Wang, "Particle effect on breakdown voltage of mineral and ester based transformer oils", IEEE Conf. Electr. Insul. Dielectr. Phenomena (CEIDP), Quebec, Canada, pp. 598-602, 2008.
[14] CIGRE, "Effect of particles on transformer dielectric strength," WG17/ SC12, Jun. 2000.
[15] H. Kurita, T. Hasegawa, and K. Kimura, "Dielectric breakdown characteristics of clean oil", IEEE Int'l. Sympos. Electr. Insul., Maryland, USA, pp. 433-436, 1992.
[16] K. Miners, "Particles and moisture effect on dielectric strength of transformer oil using VDE electrodes," IEEE Trans. Power App. and Syst., vol. PAS-101, pp. 751-756, 1982.
[17] L. E. Lundgaard, D. Linhjell, and G. Berg, "Streamer/leaders from a metallic particle between parallel plane electrodes in transformer oil", IEEE Trans. Dielectr. Electr. Insul., Vol. 8, pp. 1054-1063, 2001.
[18] S. Tenbohlen, M. Koch, D. Vukovic, A. Weinläder, J. Baum, J. Harthun, M. Schäfer, S. Barker, R. Frotscher, D. Dohnal, and P. Dyer, "Application of vegetable oil-based insulating fluids to hermetically sealed power transformers", CIGRE Session 2008, Paris, France, No. A2-102, 2008.
[19] K. Farooq, "The effect of particulate and water contamination on the dielectric strength of insulating oils", IEEE Int'l. Sympos. Electr. Insul., Quebec, Canada, pp. 728 – 732, 1996.
[20] D. Martin and Z.D. Wang, "A comparative study of the impact of moisture on the dielectric capability of esters for large power transformers", IEEE Conf. Electr. Insul. Phenomena (CEIDP), Missouri, USA, pp. 409-412, 2006.
[21] I. Fofana, H. Borsi, and E. Gockenbach, "Fundamental investigations on some transformer liquids under various outdoor conditions", IEEE Trans. Dielectr. Electr. Insul., Vol. 8, pp. 1040-1047, 2001.
[22] C. Vincent, C. Benoit, and R. Olivier, "Comparative evaluation of parameters of the dielectric breakdown test on transformer oil", IEEE Int'l. Conf. Dielectr. Liquids (ICDL), Roma, Italy, pp. 337-341, 1996.
[23] "Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes", ASTM D 1816-04, 2004.
[24] "IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers", in IEEE C57.147, 2008.
[25] "Fluids for Electrotechinical Applications - Unused Mineral Insulating Oils for Transformers and Switchgears", IEC Standard 60296, 2003.
[26] "Insulating Liquids - Specifications for Unused Synthetic Organic Esters for Electrical Purposes", IEC Standard 61099, 2010.
[27] J. K. Nelson and C. Shaw, "The impulse design of transformer oil-cellulose structures", IEEE Trans. Dielectr. Electr. Insul., Vol. 13, pp. 477-483, 2006.
[28] "Synthetic Organic Esters for Electrical Purposes - Guide for Maintenance of Transformer Esters in Equipment", IEC Standard 61203, 1992.
[29] "Mineral Insulating Oils in Electrical Equipment- Supervision and Maintenance Guidance", IEC Standard 60422, 2005.
[30] X. Wang, Z.D. Wang, and J. Noakhes, "Motion of conductive particles and the effect on ac breakdown strengths of esters", IEEE Int'l. Conf. Dielectr. Liquids (ICDL), Trondheim, Norway, pp. 11-2, 2011.
[31] R. Tobazeon, "Behavior of spherical and cylindrical particles in an insulating liquid subjected to a DC uniform field", IEEE Int'l. Conf. Dielectr. Liquids (ICDL), Baden-Dattwil, Switzerland, pp. 415-420, 1993.
[32] N. G. Trinh, C. Vincent, and J. Regis, "Statistical dielectric degradation of large-volume oil-insulation", IEEE Trans. Power App. and Syst., Vol. 101, pp. 3712-3721, 1982.
[33] S. Itahashi, H. Mitsui, T. Sato, and M. Sone, "State of water in hydrocarbon liquids and its effect on conductivity", IEEE Trans. Dielectr. Electr. Insul., Vol. 2, pp. 1117-1122, 1995.
[34] O. Koreh, K. Torkos, M. Bashir Mahara, J. Boressay, and V. Izvekov, "Study of water clusters in insulating oils by Fourier transform infrared spectroscopy", IEEE Trans. Dielectr. Electr. Insul., Vol. 5, pp. 896-902, 1998.
[35] W. G. Chadband, "The electrical breakdown of insulating oil", IEEE J. Power Eng., Vol. 6, pp. 61 - 67, 1992.
[36] K. H. Weber and H. S. Endicott, "Area effect and its extremal basis for the electric breakdown of transformer oil", IEEE Trans. Power App. and Syst., Vol. 75, pp. 371-381, 1956.
[37] J. K. Nelson, B. Salvage, and W. A. Sharpley, "Electric strength of transformer oil for large electrode areas", IEE Proc., Vol. 118, pp. 388-393, 1971.
[38] H. Goshima, N. Hayakawa, M. Hikita, H. Okubo, and K. Uchida, "Weibull statistical analysis of area and volume effects on the breakdown strength in liquid nitrogen", IEEE Trans. Dielectr. Electr. Insul., Vol. 2, pp. 385-393, 1995.
[39] W. Hauschild and W. Mosch, *Statistical Techniques for High-voltage Engineering*. London, UK: Peter Peregrinus Ltd., 1992.

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