

Statistical Analysis of the AC Breakdown Voltages of Ester Based Transformer Oils

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ABSTRACT

Recent decades have seen the rapid and successful deployment of ester oils as transformer dielectrics. When evaluating the compatibility of ester oils with existing transformer insulation designs, it is essential to not only compare the mean breakdown voltages of the oils, but also to consider the role of dispersion and thus the withstand voltage levels (with the acceptable breakdown likelihood). Insulation designers sometimes estimate the withstand voltage of mineral oil from the dispersion of the data, assuming that the breakdown voltages of the oil follow a parametric distribution. However, there is a lack of discussion as to whether this method would be suitable for estimating the withstand voltages of ester oils. This paper uses samples of breakdown voltages of a synthetic ester, a natural ester and a mineral oil to analyze their distributions, and discusses the applicability of using Weibull and Gaussian distributions to estimate the withstand voltages of the esters. It is found that the distributions of ester breakdown voltages, in particular the lowest breakdown voltage, are similar to those of mineral oil. Consequently there is evidence that from the ac withstand voltage point of view the tested esters are compatible for the use in power transformers.

Index Terms — Dielectric breakdown, oil insulation, statistics, power transformers.

1 INTRODUCTION

RECENTLY ester oil dielectrics have been introduced as substitutes for mineral oil for use in power transformers [1-6]. These oils have several advantages over other transformer oils as they are non-toxic, more biodegradable and less flammable. Oil refiners generally provide a mean oil dielectric strength although the breakdown voltage of a dielectric material is a statistically distributed quantity [7-8]. The role of distribution and dispersion is not always considered when comparing the ac breakdown voltages which may result in invalid comparisons.

The statistical nature of dielectric breakdown voltages presents transformer designers a challenge, so the insulation is designed around a withstand voltage with an additional safety factor [9]. Furthermore, the withstand voltage of insulation is regarded not as a fixed value but as a statistical variable corresponding to a low breakdown probability [8].

Statistical techniques can be used to estimate the lowest likely breakdown voltage from the dispersion of the ac breakdown voltage data. This involves assuming that the dielectric failure follows a distribution and estimating the withstand voltage at the required probability. Examples include Perrier applying the Gaussian distribution to estimate the 0.1% probability of failure of a synthetic ester [10-12] or Lick applying the Weibull distribution to estimate the 1% probability of breakdown voltage of mineral oil [13].

When using esters as substitutes for mineral oil, if the dispersion of breakdown voltages is dissimilar then the margin of safety required in transformer insulation design may be different. Therefore it is important to test whether the breakdown voltages of esters behave in a way that is statistically similar to mineral oil.

In this paper samples of one hundred ac breakdown voltages of esters and mineral oil are analysed to compare their statistical distributions, in particular whether the lowest observed breakdown voltages are different. The Weibull and Gaussian distributions are then used to discuss the similarity of the breakdown voltage distributions of these oils. All of the statistical techniques used are found in commonly available software packages. For this work Matlab 6.5 and Microsoft® Office Excel 2003 with the Analysis Toolpak add-in and Analyse-IT™ version 1.73 were used.

2 THE NATURE OF DIELECTRIC FAILURE

Many factors influence the breakdown voltage of a dielectric [14-15]. Kulkarni notes that “the breakdown voltage of a dielectric material is a statistically distributed quantity which is a function of its physical/chemical properties and impurities present in it” [7]. A frequently used model is the weak link theory [16-17] where impurities and particles are swept into regions of high electric stress by dielectrophoretic forces [7]. These

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impurities and particles tend to line along the electric field lines creating a weak link in the oil gap. Adamczewski notes that the dielectric strength of oil can improve with repeated breakdowns, as discharges remove “weak links” such as gas bubbles and impurities from the liquid and electrode surface [14]. Naidu assumes that each breakdown is an independent event due to liquid self healing [18], although care must be taken to ensure that sufficient time is given to allow breakdown products to disperse and gas to expel [19].

3 APPLICATION OF STATISTICS TO BREAKDOWN VOLTAGE DATA

Statistical techniques, parametric and non-parametric, have been extensively applied to dielectric failure [20-24]. Parametric tests assume that the data can be modeled by a theoretical distribution whereas non-parametric tests do not make this assumption. Non parametric tests may be considered more applicable in cases where the adherence of the data to a distribution can not be assumed. However, as Rees notes, non-parametric tests are less powerful than the corresponding parametric tests [25].

Two common parametric distributions are the Gaussian and Weibull distributions. When applied to statistically analyse the breakdown voltages of a dielectric material, the withstand strength is often defined as the voltage at which the risk of breakdown is considered at an acceptably low degree. This can be calculated assuming the Gaussian distribution using the mean (equation (1)) and standard deviation (equation (2)) of a sample of data. Gaussian distribution assumes the data is symmetrically distributed around the mean and there are a certain number of extreme values, or outliers, around the distribution. Data symmetry is quantified by the skewness (equation (3)) and the quantity of extreme values is given by the kurtosis (equation (4)). Given that the standard deviation of the data is calculated from the entire sample of data, and that it is only the area of the graph to the left of the mean which is used to estimate the withstand voltage, asymmetry will reduce the accuracy of the withstand voltage estimation if Gaussian distribution is assumed, making a Gaussian distribution invalid at low probability of breakdown although it is applicable at high probabilities. Moreover, Gaussian distribution does not take into account the actual mechanism of failure.

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \tag{1}$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2} \tag{2}$$

$$s = \frac{\sqrt{n} \sum_{i=1}^n (X_i - \bar{X})^3}{(\sum_{i=1}^n (X_i - \bar{X})^2)^{3/2}} \tag{3}$$

$$g = \frac{n \sum_{i=1}^n (x_i - \bar{x})^4}{(\sum_{i=1}^n (x_i - \bar{x})^2)^2} \tag{4}$$

In 1951 Weibull published his analysis on providing a distribution to model failure [26], where it was proposed that the failure is caused by a weak link, as for a chain which will fail if any of its links fail. This can be expressed in equation (5) where P_n is the probability of the chain failing due to $\varphi(x)$, a function of the load x .

$$P_n = 1 - e^{-n\varphi(x)} \tag{5}$$

Morcus believes that the Weibull distribution is often used to model breakdown voltages as it seems to fit the data better than other distributions [8].

Gumbel investigated the breaking strength of materials assuming that flaws are distributed randomly and independently [27]. The local distribution of the flaws, with respect to their size, is also random. The cumulative Gumbel distribution function is listed in the IEEE Guide for the Statistical Analysis of Electrical Insulation Voltage Endurance Data [28], as given in equation (6), where u is the location parameter and b is the scale parameter.

$$F_G(t) = 1 - e^{-e^{\frac{t-u}{b}}}; -\infty \leq t \leq +\infty \tag{6}$$

Lewis and Ward assumed that, when a stress, E , is applied to electrodes in a dielectric liquid, breakdown events are initiated randomly at a mean rate $f(E)$ [29]. They treated the time lag between the application of an electric field and the initiating event leading to breakdown as a statistical quantity which is a function of the electric stress. After studying the mean rate of occurrence of breakdown events, the authors proposed that the $f(E)$ can be expressed in the form shown in equation (7), where A and B are constants which depend on the state of the liquid.

$$f(E) = Ae^{(BE)} \tag{7}$$

Suehiro et al analysed breakdown voltages obtained from superfluid liquid helium with a temperature lower than 2 K [30], and found that the dc breakdown strength fitted the Weibull distribution in equation (8), where m is the shape parameter and E_0 is the scale parameter.

$$P_e = 1 - e^{-\left(\frac{E}{E_0}\right)^m} \tag{8}$$

Goshima et al examined the effects of the electrode area and liquid volume on the breakdown voltage of liquid nitrogen [31]. Statistical analysis of the results was carried out using the Weibull distribution in equation (9), where E_m is the applied electric field and v/v_0 represents the number of weak points in the liquid volume.

$$p = 1 - e^{-\left[\frac{v}{v_0} \left(\frac{E_m}{E_0}\right)^m\right]} \tag{9}$$

Both Suehiro and Goshima studied the breakdown voltages of ‘pure’ liquids and thus would not have observed the effects of the impurities found in industrial quality transformer oils.

Kupershtokh et al described the probability of breakdown using a macroscopic approach based on the probability density of streamer inception on a small element of electrode area in a

short interval of time [32]. The distribution proposed was described by Kupershtokh as being close to the Weibull distribution.

4 EXPERIMENTAL WORK

The aim of this investigation was to determine, despite similar mean breakdown voltages, whether low voltage breakdown events in dry esters were more or less common than in mineral oil. This is considered important as the insulation of a transformer is designed around a withstand voltage rather than the mean breakdown voltage. The mineral oil under test was Nytro 10 GBN, the natural ester was FR3 and the synthetic ester was Midel 7131.

The oils were individually degassed and dried at less than 1 kPa for 2 days at 80 °C, then were given a further day to cool to ambient temperature under vacuum conditions. Note that the oil, although degassed and dehydrated, was not filtered and the number of particles remained the same as what come through after the manufacture process.

A Baur DPA75 oil breakdown tester was used to measure ac breakdown voltages, as per ASTM D1816 [33], using brass spherically capped electrodes of the VDE specification 0370. These electrodes had a diameter of 36 mm. The electrode gap was set to 1 mm. The voltage ramp rate was 0.5 kV/s and there was a 1 minute stir time between breakdowns. Either five or ten breakdowns were performed per set depending on their dispersion as per the standard guideline. All measurements were performed at room temperature.

To give a large sample of data, at least one hundred breakdowns were obtained. The same sample of oil was used throughout the 100 breakdowns, since The Baur DPA75 tester has flash detection which minimized oil degradation caused by multiple breakdowns.

It is known that the relative humidity of oil affects the breakdown voltage [34]. Therefore, the moisture levels of the oils were obtained by Karl Fischer titration (Metrohm 684 Coulometer with 832 Thermoprep oven) and are given along with the relative humidity in Table 1.

The relative humidity of oil is a better indicator of the wetness of the oil and its affect on the dielectric properties than absolute moisture content. There was a concern that these oils might increase gain in moisture as the investigation progressed, but this was found not to have occurred by comparing the moisture contents before and after tests. There was no noticeable increase in the moisture content of mineral oil while the synthetic ester, the most hygroscopic, showed an increase of 25 ppm. At room temperature, 25 ppm moisture increase in the synthetic ester equates to a 1% increase in relative humidity. Low moisture uptake rates can be explained by the relatively short experiment duration, which was roughly 6 hours in a sealed oil bath.

From the results given in a recent study [35] it is unlikely that these low levels of moisture would affect the mean breakdown voltage of the oils.

Table 1. Moisture content of oils.

Oil	Moisture content (ppm)	Oil relative humidity at 20°C (%)
Mineral oil	9	17
Natural ester	35	3
Synthetic ester	59	2

The breakdown voltage results are plotted in Figures 1–3.

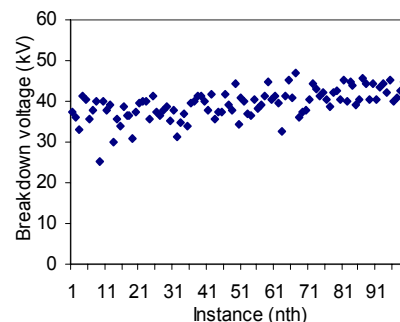


Figure 1. Distribution of mineral oil breakdown voltage data.

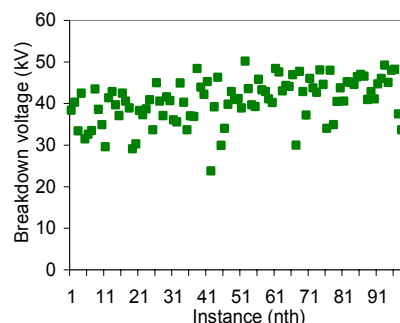


Figure 2. Distribution of natural ester breakdown voltage data.

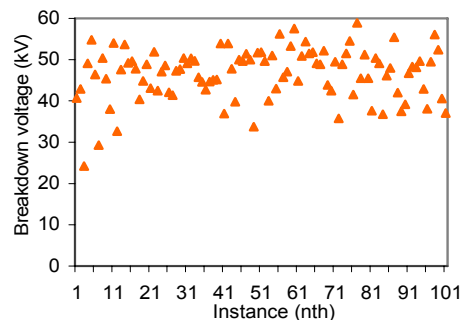


Figure 3. Distribution of synthetic ester breakdown voltage data.

4.1 ANALYSIS OF DATA

The breakdown voltages are plotted as histograms in Figures 4-6. The mean, standard deviation, kurtosis and skewness of the sample populations are given in Table 2.

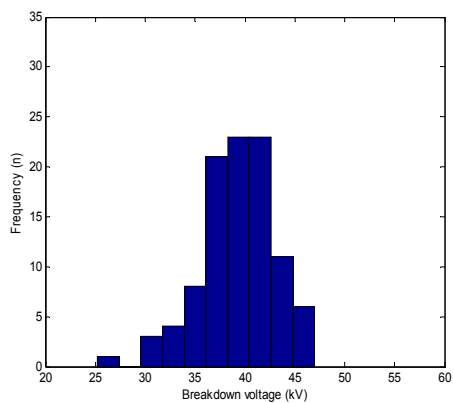


Figure 4. Probability density plot of mineral oil breakdown voltages.

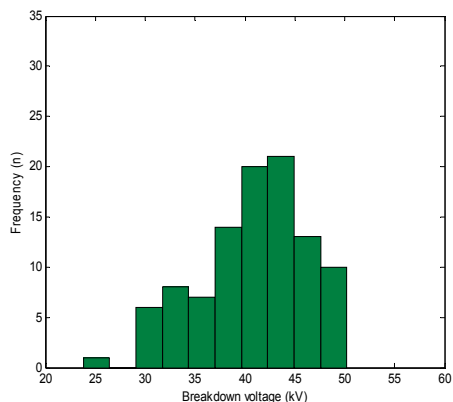


Figure 5. Probability density plot of natural ester breakdown voltages.

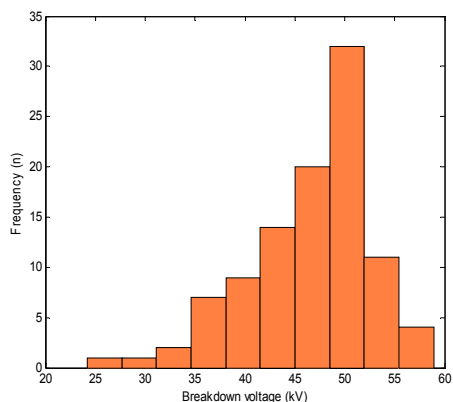


Figure 6. Probability density plot of synthetic ester breakdown voltages

Table 2. The mean, standard deviation, kurtosis and skewness of the sample populations obtained during the investigation.

Oil	Mean (kV)	Standard deviation (kV)	Kurtosis	Skewness
Mineral oil	39	3.7	4.36	-0.73
Natural ester	41	5.3	3.01	-0.60
Synthetic ester	47	6.2	3.98	-0.82

The Gaussian distribution assumes that skewness = 0 and kurtosis = 3. All samples are skewed, which will reduce the accuracy of using the standard deviation to estimate the withstand voltage. The kurtoses of the samples are greater

than 3, indicating that the breakdown voltages are leptokurtic, that is, extreme values occurred more often than predicted by the Gaussian distribution. The Weibull distribution can be expected to produce a better theoretical curve for modeling breakdown voltages as it does not make assumptions of the skewness and kurtosis.

When analysing the histograms the following conclusions can be made:

- The lowest breakdown voltages were all similar around 25kV.
- IEEE standard 62-1995 for diagnostic field testing of electric power apparatus recommends that the minimum mean dielectric breakdown voltage for oil in equipment having nominal voltage rating of 69 kV or higher is 26 kV. Breakdowns occurring in esters around 26 kV appear to be around as frequent as those occurring in mineral oil. Therefore esters are performing as effectively as mineral oil.
- The synthetic ester has the most skewed distribution. Although this ester has a higher mean breakdown voltage than mineral oil, the lowest breakdown voltages are similar.

4.2 ADHERENCE TO GAUSSIAN DISTRIBUTION

The Shapiro Wilk test assesses the likelihood of the hypothesis that a sample is normally distributed being correct [36-38]. The statistic *calc w* is calculated for the sample and is then compared to a tabulated value, *tab w*, to estimate the probability that the distribution is normal. If this probability is higher than the chosen level of significance, by convention 5%, then the sample is judged to be normally distributed.

It can be seen in Table 3 that this test rejects the hypothesis that the breakdown voltages for these oils are normally distributed. This is undoubtedly due to the distributions of breakdown voltages being skewed.

Table 3. Summary of performing the Shapiro Wilk test for normality.

Oil	Calculated w	Probability that sample is normally distributed (%)	Conformance to normality
Mineral oil	0.96	0.9	REJECTED
Natural ester	0.97	1.8	REJECTED
Synthetic ester	0.95	0.1	REJECTED

The outcome of this is that the Gaussian distribution does not accurately model breakdown as earlier discussed.

Quantile-Quantile plots can be used to compare the sample of data to an expected Gaussian distribution using the mean and standard deviation calculated from the data, shown in Figures 7-9. All three oils show deviations at the tails, demonstrating the inaccuracy of using the Gaussian distribution to model the data at low probabilities. The data deviates from the distribution at between 5% and 10% depending on the oil.

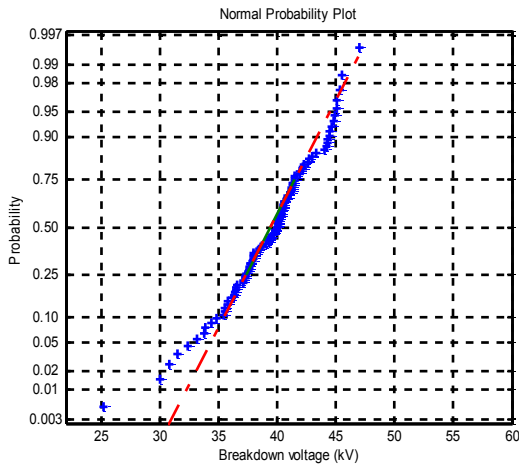


Figure 7. Normal probability plot of mineral oil.

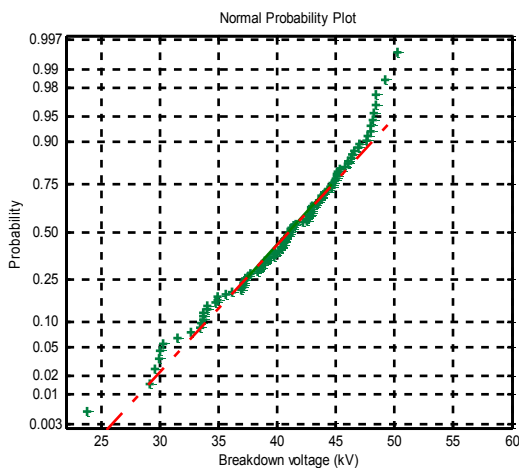


Figure 8. Normal probability plot of natural ester.

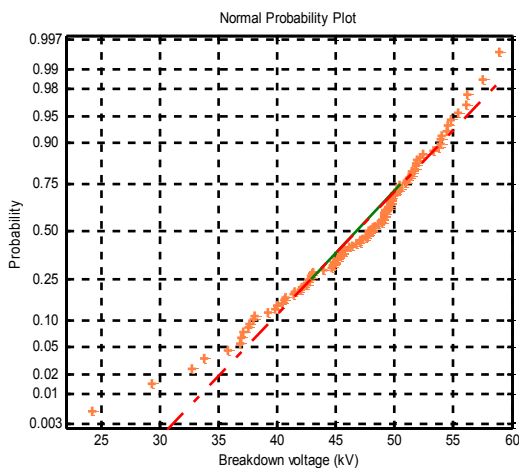


Figure 9. Normal probability plot of the synthetic ester.

It is notable that although the synthetic ester has the highest mean voltage, the first quantile is around the same voltage as the first quantile of the other oils. The implication of this is that insulation structures used for mineral oil should be appropriate for use in a transformer filled with this ester.

4.3 ADHERENCE TO WEIBULL DISTRIBUTION

Figures 10-12 shows the Weibull distribution being used for modeling the distributions. Similarly to when the Gaussian distribution is applied, both esters have produced shallower trend lines than the mineral oil. However, as the mean breakdown voltages are higher than that of the mineral oil, the lowest breakdown voltages of the esters are not lower than those of the mineral oil.

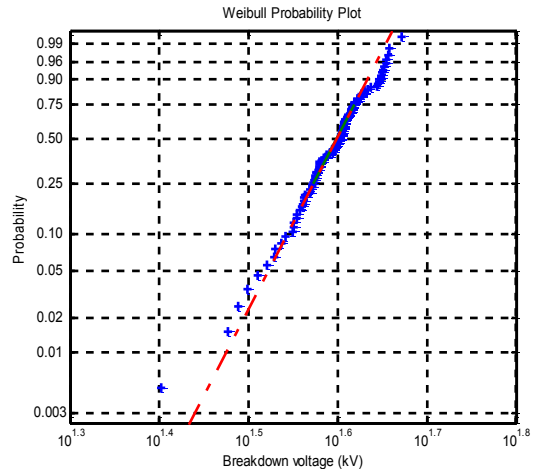


Figure 10. Weibull distribution of mineral oil.

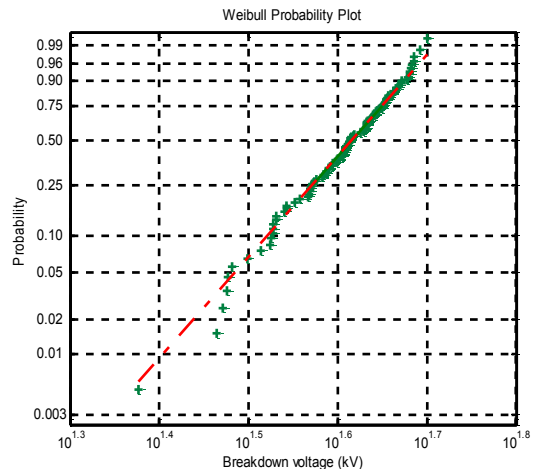


Figure 11. Weibull distribution of natural ester.

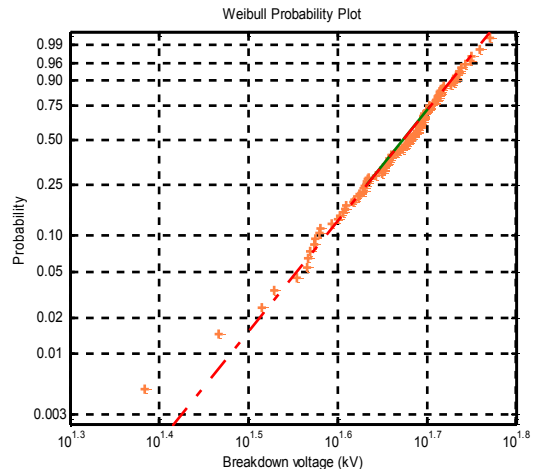


Figure 12. Weibull distribution of the synthetic ester.

On first sight the samples tend to adhere better to the Weibull distributions. As with applying the Gaussian distribution, the accuracy decreases with reducing probability. Both esters perform similarly to mineral oil, with the 1% value being around $10^{1.4}$, equating to 25 kV.

4.4 COMPARISON WITH NON PARAMETRIC TESTS

It can be seen that both distributions become inaccurate at low probabilities. This can be due to the kurtosis of the sample as well as fewer observations being available at low probabilities. Non parametric tests were then applied to count the quantiles and find the probability of an event occurring at the n^{th} measurement. The data is shown in Table 4.

All of the lowest breakdown voltages, i.e. the breakdown voltage value with 1% probability, are below the levels predicted by both parametric distributions. This is a concern since this demonstrates that sufficient safety margin is required to add on when using the withstand voltage of oil derived from these parametric distributions in insulation design.

Table 4. Comparing withstand voltages of non-parametric and parametric methods.

Probability	Non parametric (kV)	Gaussian distribution (kV)	Weibull distribution (kV)
Mineral oil			
U_{50}	40	39	41
U_{10}	35	36	37
U_5	32	35	35
U_2	30	33	33
U_1	25	32	29
Natural ester			
U_{50}	41	41	43
U_{10}	34	34	36
U_5	30	32	33
U_2	29	30	29
U_1	24	28	26
Synthetic ester			
U_{50}	48	47	50
U_{10}	38	39	42
U_5	36	37	39
U_2	29	35	34
U_1	24	34	30

At the 1% risk of breakdown, the Weibull distribution tends to give closer results to that of the non-parametric test than the Gaussian distribution.

Since neither Weibull nor Gaussian distribution accurately provide the voltage at 1% risk of failure from a sample size of 100 data, estimating the U_1 voltage from a 5, 6 or 10 point data sample as per ASTM D1816 or IEC 60156 is unlikely to provide a reasonable result.

5 WITHSTAND VOLTAGE OF OILS

As discussed, rather than considering the withstand voltage to be a value where the oil will not fail as a dielectric, the withstand voltage should be considered as a level where the risk of failure is acceptably low. As these oils are leptokurtic the possibility of extreme, unforeseen failures at low voltage is always present. Therefore, a

withstand voltage value, or more precisely a withstand electric field in terms of kV/mm, should be always used with sufficient safety margin by the insulation designer.

The lowest observed breakdown voltages of the esters are comparable to that of the mineral oil (Table 4) with only 1 kV difference. The largest difference between the non parametric and parametric distributions was found in the case of the synthetic ester. This is due to the synthetic ester having the most skewed distribution, as skewness decreases the accuracy of the Gaussian distribution.

Withstand voltages for 1mm oil gaps have been studied thoroughly in this paper, for transformer insulation design, ester oil gaps varying from a few mm to tens mm distances, require their withstand voltages to be determined.

6 CONCLUSION

From the histograms it can be concluded that the ac breakdown performance of the esters, at low probabilities, was comparable to mineral oil. The lowest breakdown voltage of esters was also similar to that of mineral oil. Therefore, when considering transformer insulation, it is likely that designs intended to use mineral oil will be suitable for esters.

The kurtoses of the esters were slightly lower than that of mineral oil, indicating that outlying ester breakdown voltages are unlikely to be more frequent than when occurring in mineral oil. This suggests esters are likely not to be less reliable than mineral oil as dielectrics.

All of the samples of breakdown voltages were skewed, consequently the Gaussian distribution to model the breakdown voltage distribution, especially for calculating the withstand voltages at low probabilities, is not as appropriate as the Weibull distribution. This is explained since the Gaussian distribution makes the assumptions that the skewness is 0 and the kurtosis is 3 whereas the Weibull distribution does not make these assumptions.

Considering the effectiveness of esters as dielectrics, this shows that these oils can be as capable as mineral oil in acting as transformer insulation.

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