A Comparative Study of the Impact of Moisture on the Dielectric Capability of Esters for Large Power Transformers

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Abstract: There is debate as to whether esters will be suitable replacements for mineral oil in large power transformers, such as those found on the transmission system of the UK. Research has reported that ester oils operate advantageously when compared to transformer mineral oil. However, moisture is known to affect the dielectric capabilities of oils. This paper presents research investigating the impact of moisture on the dielectric properties of esters compared to mineral oil. It was found that AC dielectric strengths of esters are higher than mineral oil over the range of moisture levels selected. When considering the lightning impulse breakdown voltage of esters, although dry mineral oil has higher breakdown voltages than esters, it is quickly reduced to a level comparable to esters with increasing moisture.

Introduction

The oil is one of the sensitive components in transformer insulation, as the "Reliability of new insulation is determined by dielectric strength of the oil" [1]. In addition oils may be used in transformers for decades without maintenance, heightening the need for studies into the effects of the processes which may lead to the degradation of the oil dielectric performance. The effect of moisture is one such process. This is particularly important in the case of 400kV power transformers as high operating voltages require tight control of factors which influence the dielectric performance. Free breathing power transformers typically use an air breather to dry the air, so under normal operation the oil will not absorb moisture from the atmosphere. However, moisture is created during cellulose paper degradation [2]. With mineral oil, it has been shown that with more moisture the breakdown voltage decreases and the dielectric dissipation factor increases [3] [4]. This paper compares examples of synthetic and natural esters to mineral oil. The dielectric properties of unused esters have similar AC breakdown voltages and dielectric dissipation factors to mineral oil, as shown in table 1.

Both CPS [5] and Fofana et al [6] report the AC breakdown voltage of esters as a function of water content, however as different standards are used comparison is difficult. Two IEEE standards have been found providing limits for minimum AC breakdown voltage, Std 62-1995 "Guide for Diagnostic Field Testing of Electric Power Apparatus" and C57.106.2002 "Guide for Acceptance and Maintenance of Insulating Oil Equipment". Using ASTM D1816 with 1mm gap the 62-1995 limit for equipment over 345kV is 26kV and the C57.106-2002 limit for equipment over 230kV is 30kV. In addition to comparing ester breakdown voltage with mineral oil, the breakdown voltages will be compared with IEEE limits to evaluate suitability.

Table 1: Breakdown voltages of ester oil reported by manufacturer

Oil and standard	Breakdown voltage (kV)	Dielectric dissipation factor (%)
ASTM standard	D1816	D924
Mineral oil	35 (0.04" gap)	0.1 @100°C
Natural ester	56 (0.08" gap)	0.05 @ 25°C
IEC/BS standard	IEC 60156	BS 5735
Mineral oil	40-60(2.5mm gap)	<0.1 @ 90°C
Synthetic ester	>75 (2.5mm gap)	<0.6 @ 90°C

The impulse breakdown voltage is important as a flashover in the oil may in turn damage the transformer solid insulation. Currently, there is little data on the lightning impulse breakdown voltages of ester oils and none has been found considering the impact of moisture. ASTM D3300 "Standard test method for dielectric breakdown voltage of insulating oils of petroleum origin under impulse conditions" is used. Oommen reports impulse breakdown voltages [7] using a needle configuration, different to the sphere to sphere configuration used by CPS and in this investigation.

Table 2: Reported impulse breakdown voltages to ASTM D3300

Oil and source	Breakdown voltage (kV)	Electrode configuration
Oommen		Needle negative
Natural ester	116	
High temp mineral oil	145	
CPS		Sphere to sphere 1" gap
Natural ester	226	

The impact of moisture

Several researchers report the mechanism and understanding behind moisture uptake of mineral oil. Water exists in oil in fixed, free and dissolved states, however this investigation will be restricted to dissolved moisture. The amount of water that may exist in the dissolved state, at a constant temperature, is directly proportional to the air relative humidity. Increasing temperature will raise the quantity of moisture that may be dissolved in oil. When compared to mineral oil, ester fluids generally have higher moisture saturation limits, as shown in table 3 data provided by manufacturer and Oommen [8].

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Table 3 Comparison of water solubility of transformer oils

Oil	Solubility @ 20°C (ppm)
Mineral oil	55
Natural ester	1,100
Synthetic ester	2,700

Relative humidity

The moisture content of a liquid can be expressed in terms of relative humidity [3]. This is a ratio of the weight of the moisture content in the sample, to the maximum soluble moisture content that may exist in the sample at a given temperature and pressure.

$$W_{REL} = \frac{W_{MoistureContent}}{W_{SolubleMoistureContent(T)}} \tag{1}$$

Investigation

The aim of these investigations was to determine comparatively the dielectric effect of moisture on oil. Low oil relative humidities were suggested by industry to be realistic of a transformer environment, when oil is too wet it can be expected for the Utility to replace the oil. In this investigation a top limit of 30% oil relative humidity was chosen.

Procedure

A desiccator and glycerol solution were used to vary the oil moisture content as per ASTM D5032. The proportion of glycerol in solution can control the relative humidity of the air by Raoult's law. In an enclosed container, the vapour pressure of water will increase to 2330 Pa, or 100% RH at 20°C and 1000mbar (100kPa). When a non-volatile solute is added to water, the vapour pressure of the solution is equal to the vapour pressure of the pure solvent at that temperature multiplied by its mole fraction. When glycerol is added, as glycerol has a negligible vapour pressure, the vapour pressure of the solution will become equal to the vapour pressure of the mole fraction of water in the solution. To convert from weight to mole fraction, the weight can be divided by the molar weight, which in this case is 18grams/mole for water and 92.1grams/mole for glycerol (2). With the air relative humidity controlled, this will in turn control the moisture content of the oil. Petri dishes were used to give very large surface areas for moisture uptake. After conditioning the oil from several Petri dishes were poured into a bottle and left for a week to assist moisture uniformity in the bottle.

$$RH = \left(\frac{\dfrac{Weight_{Water}}{18}}{\dfrac{Weight_{Glycerol}}{92.1} + \dfrac{Weight_{Water}}{18}} \right) \tag{2}$$

It is noted that the hygroscopy of an oil is dependant on the temperature, for this investigation the laboratory air temperature was between 20 and 25°C depending on the time of day. The first moisture samples, which were around 2% relative humidity, were obtained by vacuuming the sample to less than 10mbar. Difficulties were noted with decreasing moisture levels in the desiccator to less than 10% air humidity. The exact moisture content of each oil was determined by Karl Fischer analysis. A Metrohm 684 Coulometer with oven were used to provide accurate moisture readings however it is noted that there will be a minor error due to variations of background moisture. Two measurements were taken then averages found.

AC breakdown voltage comparison

A Baur DPA75 was used for AC breakdown voltage measurements as per ASTM D1816 with partial sphere electrodes and 1mm gap. In total 4 samples of 5 breakdowns were taken to give 20 breakdown voltages in total. Care must be taken allowing sufficient time for air bubbles to be expelled when pouring esters into the test cell. The esters tested have higher viscosities and lower interfacial tensions than mineral oil, leading to slower expulsion of bubbles. It is noted that ASTM D1816 has not been verified for oils over 19cSt at 40°C viscosity, and that esters are more viscous, however the manufacturer believes that this standard is suitable with a 15 minute stand time after pouring to give the bubbles of air sufficient time to escape. The AC breakdown voltages were found as functions of absolute moisture and relative humidity.

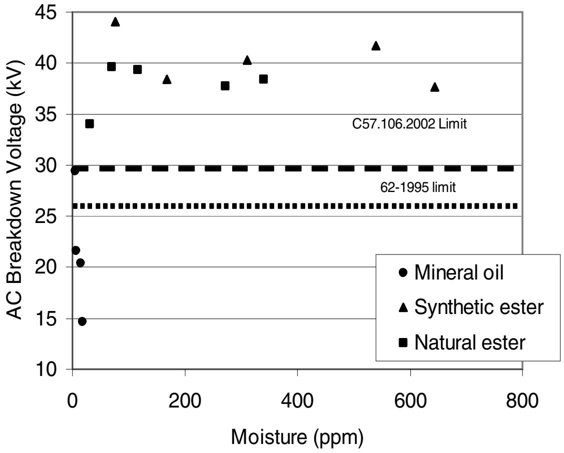

Figure 1: Oil breakdown voltages as a function of moisture

The results show that the mean breakdown voltages of esters are higher than that of mineral oil. Whereas the graphs illustrate a steep drop in mineral oil AC breakdown voltage, esters do not show a notable decrease with the levels of moisture tested. When considering an ester testing guide [5], although care must be taken when directly comparing values due to differences in electrode spacing, the natural ester results agree with the guide in that ester is not affected by moisture levels up to 30% or 330ppm. With a 1mm gap the natural ester breakdown voltages were between 37 and 40kV up to 30% RH, which is comparable with the natural ester testing value of between 60 and 75kV for 2mm gap.

The results for the synthetic ester are comparable to Fofana as moisture does not significantly affect the ester breakdown voltage until around 20% RH. Unfortunately, as Fofana did not use ASTM D1816 as the breakdown standard it is difficult to compare actual values obtained in this investigation with Fofana.

At 5ppm moisture content the mineral oil had a breakdown voltage of 30kV When comparing AC breakdown voltage with the two IEEE guides, moisture levels for mineral oil over 10% to 20% relative humidity will cause standard non-compliance. Therefore, mineral oil has to be dry to comply with standards. The graphs show that esters have AC breakdown voltages in excess of IEEE standards at moisture levels up to 30% relative humidity.

The standard deviations of both esters appear to be higher than that of the mineral oil although this may be due to effects pertaining to the ASTM method rather than directly attributable to moisture. Further testing has indicated that the size and shape of the electrodes has an important influence over the reproducibility of the test results. This phenomenon will be investigated in a more detailed study.

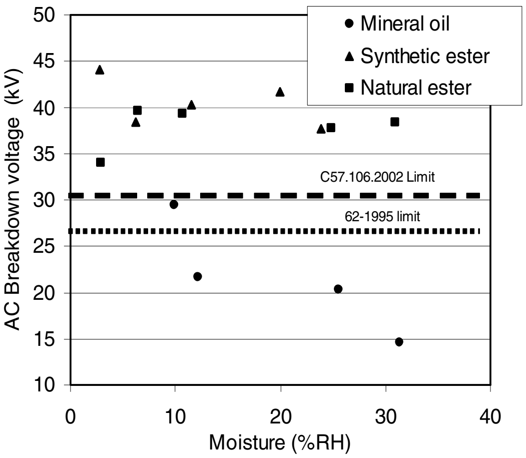

Figure 2 Oil breakdown voltages as a function of relative humidity

Without further investigation it is difficult to determine whether the breakdown voltage distributions of wet and dry oils are actually statistically different.

Table 4: AC breakdown voltage means and standard deviations

Oil and moisture content	Mean breakdown (kV)	Standard deviation (kV)
Mineral oil		
5ppm 10% RH	29	4.5
7ppm 12% RH	22	4.0
14ppm 25% RH	15	4.1
17ppm 31% RH	20	3.7
Natural ester		
31ppm 2.8% RH	34	3.7*
70ppm 6.4% RH	40	4.4*
117ppm 10% RH	39	5.2*
273ppm 24% RH	38	5.8*
340ppm 30% RH	38	7.5*
Synthetic ester		
75ppm 2.8% RH	44	5.3*
168ppm 6.7% RH	38	9.1*
312ppm 12% RH	40	10.7*
539ppm 21% RH	42	10.8*
644ppm 25% RH	38	10.6*

* =Figures for natural and synthetic ester require further investigation – see text

Lightning impulse breakdown comparison

A Haefely 10 stage impulse generator was used, in 6 stage configuration, to provide 1.2µs/50µs negative voltage transients simulating a lightning strike as per ASTM D3300. A test cell with 12.7mm diameter spherical to spherical brass electrode configuration with 3.8mm gap was used. As per ASTM D3300, a low voltage transient was applied and raised in steps of -10kV until flashovers were observed. It is noted that ASTM D3300 is for oils of petroleum origin, however ASTM D6871 specification for natural ester fluids recommends D3300. The lightning breakdown voltages were found as functions of absolute moisture and relative humidity.

The results show that the impulse breakdown voltage for dry mineral oil is higher than that of the dry esters. There is a similarity with Oommen, who notes that mineral oil has a higher impulse breakdown voltage than an ester. However, no further comparison can be made as the ester is a different product with a different electrode configuration.

The value provided by CPS is higher than the impulse breakdown voltages measured, however CPS used a larger gap (1” compared to 0.15”). The mineral oil breakdown voltage decreases at a greater rate with moisture than esters. At 17ppm, or 31% relative humidity, the lightning impulse breakdown voltage of mineral oil is approximately the same as the esters. A cloud of by-products caused by repeated impulses was noted in all oils, contrasting this standard with the AC breakdown voltage method no stirrer was used to disperse breakdown by-products. This may account for the variation in results for the natural ester, which is the most viscous fluid used in this test. Currently, no standards have been found specifying levels for impulse breakdown voltages of esters in service, so it is difficult to grade ester performance. So far, no data has been found concerning how the impulse breakdown voltage of esters varies with moisture.

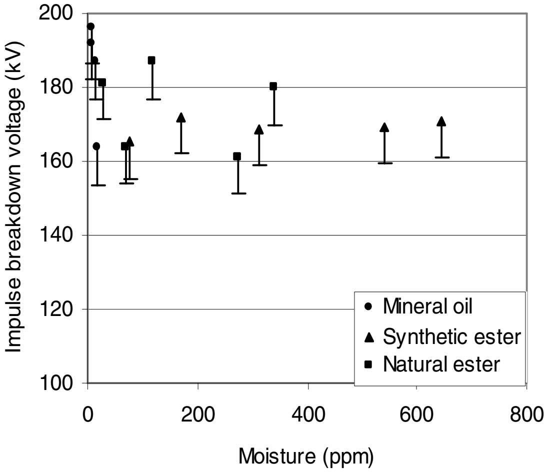

Figure 3: Lightning impulse breakdown voltage as function of absolute moisture

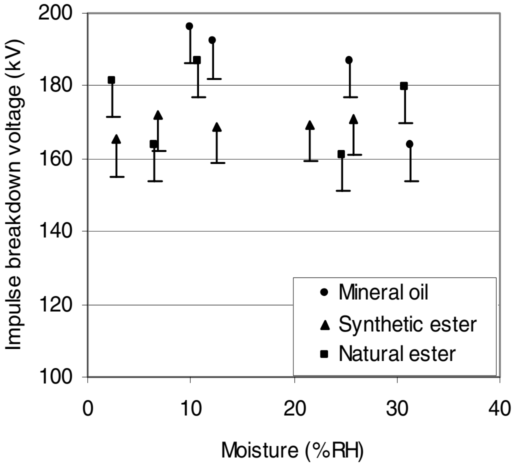

Figure 4: Lightning impulse voltage as function of relative humidity

Conclusions

Both esters used in this investigation had better AC dielectric strengths than mineral oil in terms of both relative humidity and absolute moisture content. At this stage it is unclear whether the apparent higher standard deviations of esters are due to the difficulty in establishing reproducibility of the ASTM method, or are resulting from the effect of moisture. Future work will investigate this problem in more detail.

Dry mineral oil has the highest lightning impulse breakdown voltage, however mineral oil breakdown voltage decreases rapidly with the addition of moisture. The esters tested with relative humidities less than 30% have similar lightning breakdown voltages as mineral oil with 30% humidity.

Esters exceed AC breakdown voltage levels specified by IEEE Std 62-1995 and C57.106.2002, however impulse breakdown voltage can not be compared as no value is given in either IEEE standard.

In the case of power transformers, these results infer that both synthetic and natural esters have sufficiently met the existing safety factors for AC dielectric strength in transformer insulation using mineral oil. However, further investigation would be required to determine the sufficiency of safety factors when considering lightning impulse strength.

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References

[1] V. Sokolov, D. Hanson, “Impact of Oil Properties and Characteristics on Transformer Reliability”, in TechCon Conference Proceedings, Nashville, TJH2B, 2006.

[2] C. Patrick McShane et al “Retrofilling aging transformers with natural ester based dielectric coolant for safety and life extension”, in Cement Industry Technical Conference Proceedings, Dallas, pp. 141 – 147, IEEE, 2003.

[3] I. Fofana et al “Moisture uptake of mineral oil at different air relative humidities and temperatures”, in Electrical Insulation and Dielectric Phenomena Conference Proceedings, Victoria BC, vol. 1, pp. 276 – 279, IEEE, 2000.

[4] H. Borsi, “Dielectric Behavior of Silicone and Ester Fluids for Use in Distribution Transformers”, *Transactions on Electrical Insulation*, Vol. 26 No.4 pp. 755 – 762, IEEE, 1991.

[5] Cooper Industries, *Envirotemp FR3 Fluid testing guide*, Waukesha, WI, USA, Cooper Industries Inc, 2004.

[6] I. Fofana et al, “Fundamental Investigations on Some Transformer Liquids under Various Outdoor Conditions”, *Transactions on Dielectrics and Electrical Insulation*, Vol. 8, No. 6, pp.1040 – 1047, IEEE, 2001.

[7] T.V. Oommen, “Vegetable Oils for Liquid-Filled Transformers”, *Electrical Insulation Magazine*, Vol. 18, No.1 pp. 6 – 11, IEEE, 2002.

[8] T.V Oommen et al “Biodegradable Electrical Insulation Fluids”, *in Transformer materials*, Electrical Insulation Conference Proceedings, Illinois, USA, pp 465 – 468, IEEE, 1997.

[9] L. Lewand, “Laboratory Evaluation of Several Synthetic and Agricultural-Based Dielectric Liquids”, in Doble International Client Conference Proceedings, Doble, USA, 2001

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