A Comparative Study of the Dielectric Strength of Ester Impregnated Cellulose for Use in Large Power Transformers

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Abstract: It is essential to ensure that the dielectric strength of an oil-cellulose insulation structure is not reduced when using esters to replace mineral oil in power transformers. One advantage proposed to using esters is that their higher dielectric constants, when compared to mineral oil, provide a better match to the dielectric constant of the impregnated cellulose. This results in the electric stress being reduced in the oil and increased in the cellulose, beneficial as the oil tends to have the lower dielectric strength. This paper reports the ac and impulse dielectric strengths of ester impregnated paper and pressboard. It was found that the ac withstand voltages of cellulose impregnated with ester are at least equal, or better, than cellulose impregnated with mineral oil. The lightning impulse dielectric strengths of cellulose impregnated with ester were found to be comparable to mineral oil. An analysis is given on the breakdown process of cellulose, as cellulose can fail due to either a direct puncture or discharges created in the oil wedge.

INTRODUCTION

A large amount of cellulose in the form of paper and pressboard insulation is used during the manufacture of a transformer. Cellulose acts as an insulator in regions of high electrical stress, partitions large oil gaps and provides mechanical support.

Recently, ester oils have been highlighted as environmentally friendly substitutes for mineral oil in large power transformers. To use esters in a transformer with confidence, it must be verified that the cellulose dielectric strength is maintained when being used with these fluids in combination.

Cellulose is a macromolecule, with micro-cell voids within the structure. For pressboard, layers of cellulose are pressed together with a typical quantity of 35 layers per mm. Thin channels remain in between the layers. During impregnation, oil fills the micro-cells and channels [1].

The electric stress in a composite system is shared between the oil and cellulose as a function of the dielectric constants of the materials. The ε of oil insulated pressboard can be determined by (1) [2]. K is calculated from the oil and pressboard volumes (2). In the case of 1.2g/cm^3 pressboard K = 0.54. When using mineral oil (ε = 2.2) with this pressboard density, $\varepsilon_{\text{impregnated pressboard}}$ = 4.4. Due to the ratio of relative dielectric constants, the electric stress is higher across the oil than across the cellulose. When the electric stress across the oil reaches a certain level, discharges occur in the oil, which can damage the cellulose eventually leading to conductive track formation and dielectric failure.

$$\varepsilon_{\text{Impregnated Pressboard}} = \varepsilon_{\text{Fibre}} \cdot \left[1 - K^2 \left(1 - \frac{1}{1 + K \cdot \left(\frac{\varepsilon_{\text{Fibre}}}{\varepsilon_{\text{Oil}}} - 1 \right)} \right) \right] \quad (1)$$

$$K = \sqrt[3]{\frac{V_{\text{Oil}}}{V_{\text{Pressboard}}}} \quad (2)$$

On the other hand esters have a ε of 3.2, higher than that of mineral oil. Using (1), the $\varepsilon_{\text{impregnated pressboard}}$ = 4.7. Therefore, the permittivities of esters and cellulose are more evenly matched thus the electric stress should be more equally shared.

Tsukoika proposes that oils with dielectric constants close to that of the cellulose have the advantage of sharing the electric stress more equally across the materials [3]. Given that the dielectric constant of mineral oil is lower than that of the cellulose, matching dielectric constants tends to reduce the electric field in the oil and increase the field in the cellulose. This is advantageous as the breakdown voltage of cellulose is usually higher than that of the oil. Areas of particular risk in a transformer are oil-filled wedge shaped regions around conductors, as shown in figure 1. This is partly due to that the electric field around a curved surface tends to be higher than near a flat plane [4].

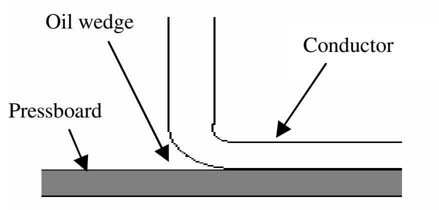

Figure 1. Location of oil wedge in transformer design

To demonstrate the effect of matching the dielectric constants, Tsukoika used low permittivity pressboard created from a blend of polymethylpentene and cellulose fibre (ε_r = 3.5). It was shown that both ac partial discharge starting voltage and impulse breakdown voltage of the low permittivity pressboard were 30% higher than when the normal cellulose was used. Therefore, Tsukoika concludes that “a clear effect on the

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breakdown strength for the low dielectric constant material was found".

Hemmer et al [5] investigated the electrical properties of vegetable oil impregnated pressboard insulation manufactured by Weidmann Transformer board. Specifically, the pressboard specimens were 1mm thickness TI and TIV types. The ac breakdown voltage was found as per IEC 243 with asymmetrical electrode arrangement contacting the specimen. 13 specimens were tested to assure statistical reliability. Hemmer concluded that the breakdown voltage for ester impregnated cellulose is slightly higher (approx 10%) than when the cellulose is impregnated with mineral oil. However, no indication of breakdown mechanism is given, i.e. whether the dielectric failure was caused by an oil wedge.

INVESTIGATION

The aim of these investigations was to measure the ac and lightning dielectric strengths of ester impregnated cellulose and compare to cellulose impregnated with mineral oil. Furthermore, the research is to ascertain whether the higher dielectric constant of the esters affects the breakdown voltage of cellulose. Two esters were selected, one being of synthetic origin and the other natural seed oil based. Three different types of cellulose were investigated, as listed in table 1.

Table 1. Cellulose types investigated

Cellulose type	Thickness
Creped Kraft tape complying with BS 5626 Part 3 Section 3.3 1982	90 micron
Pressboard complying with IEC 641-2 and 243-1	1.5mm
Pressboard complying with IEC 641-2 and 243-1	3.0mm

IMPREGNATION PROCEDURE

Cellulose was first dried for 24 hours at 105°C under a vacuum of less than 1 kPa. The oils were dried at 80°C under vacuum at less than 1 kPa for 3 days. The cellulose was then immersed in the oils. There is evidence to suggest that the higher viscosity of esters is not sufficient to affect the impregnation rate of small pieces of pressboard [6]. However to err on the side of caution the samples were impregnated for one week and maintained in oil until tests were performed.

AC BREAKDOWN VOLTAGE COMPARISON

The ac breakdown voltage was measured according to ASTM D149 [7] using type 2 electrodes which were 25mm diameter brass cylinder types. The electrode edges were rounded to a radius of 3mm, creating an environment similar to the oil wedge explained previously in figure 1. The circuit was set up as per figure 2 and could provide a maximum output of 150kV. A water resistor was used to limit the current when breakdown occurred. Tests were performed at room temperature and pressure. The voltage was applied in a step by step format, as given by method B of ASTM D149. Each step lasted 1 minute and different increments were used depending on cellulose thickness. For each oil, 5 samples of cellulose were tested. The ac tests were performed first, the oil was then changed for the lightning impulse breakdown tests.

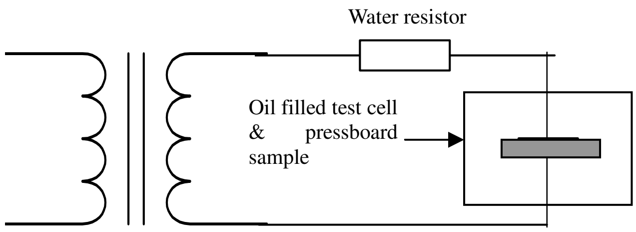

Figure 2. Circuit to measure ac dielectric strength of cellulose

Table 2. Start and step voltage levels

Cellulose type	Start voltage (kV)	Voltage step (kV)
Creped Kraft tape	2.5	2.5
1.5mm pressboard	10	5
3.0mm pressboard	10	10

RESULTS

ASTM D149 method B requires for the voltage to be recorded of the highest completed withstand level. As can be seen from figures 3-5, the performance of ester impregnated cellulose is at least equal to that of cellulose impregnated with mineral oil.

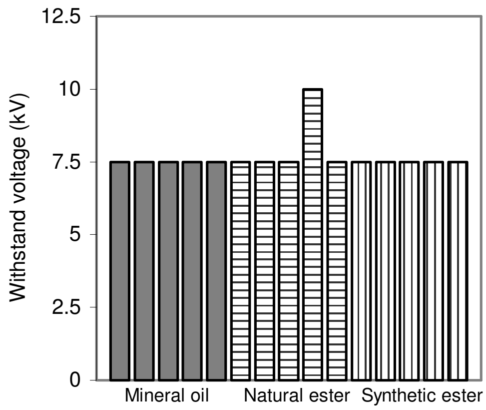

Figure 3. Breakdown voltages of impregnated Kraft paper

From a visual examination, the paper could be seen to be punctured in the region between the flat parts of the electrodes, however the pressboard tended to puncture around the edges of the electrodes, where the oil wedge is present. There was a general trend that cellulose impregnated with ester took longer to fail than when impregnated with mineral oil. The majority of the 1.5mm samples failed at 45kV, with the time taken to failure given in Figure 6. As can be seen, the pressboard impregnated in ester took longer to fail than when impregnated in mineral oil. This may infer that esters would be advantageous in situations concerning momentary over-voltages.

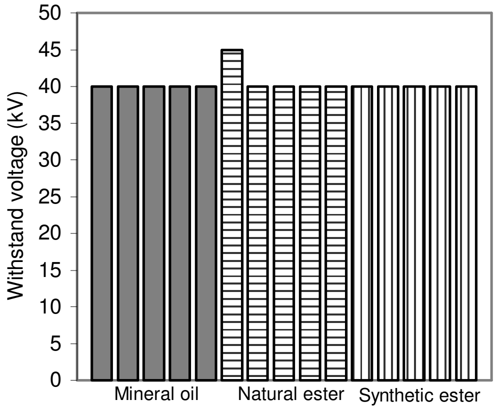

Figure 4. Breakdown voltages of impregnated 1.5mm pressboard

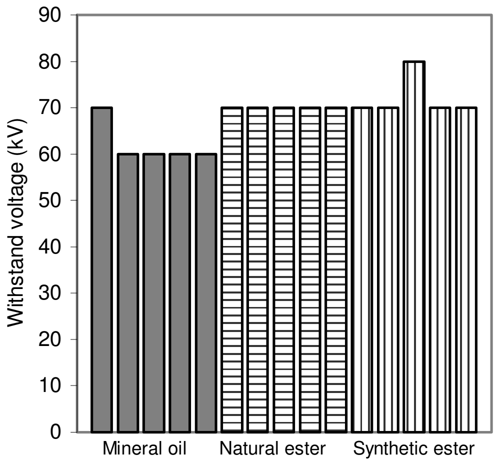

Figure 5. Breakdown voltages of impregnated 3.0mm pressboard

The 3mm ester pressboard failed at higher voltage levels. Several explanations are possible. Firstly, in the case of the esters, matching the dielectric constants of the materials will reduce the electric field in the oil so that higher voltages are required to cause breakdown in the oil wedge. Secondly, breakdown products created by breakdown of the ester may be different to those created by mineral oil. Whitehead notes that unsaturated hydrocarbons tend to absorb discharge products reducing the possibility of a breakdown [8].

The moisture content of the oil bath in the test cell was recorded at the end of the experiment, shown in table 3, as it is known that moisture in terms of percentage saturation affects the oil dielectric strength. It was regarded important to consider the role of oil moisture content due to that this may affect the process of breakdown in the oil wedge. None of the samples are considered suitably saturated to have affected the breakdown voltage of the oil [9]. The mineral oil turned yellow slightly, whereas neither of the esters discoloured. The natural ester appeared to generate large black particles whereas the synthetic ester appeared to create more gas than the other two oils.

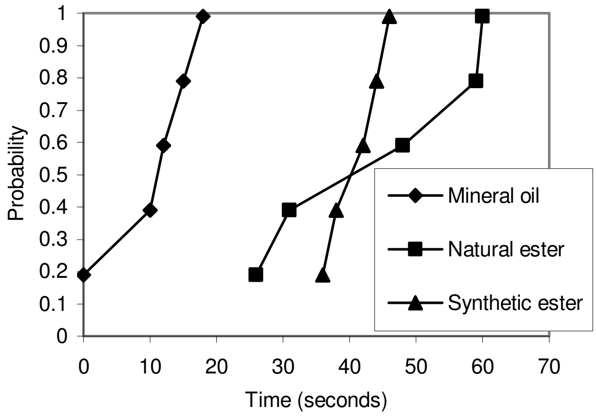

Figure 6. Time to fail for 1.5mm pressboard at 45kV

Table 3. Moisture content and percentage saturation of test samples

Oil	Moisture content (ppm)	Percentage saturation of oil at 20°C (%)
Mineral oil	6	11
Natural ester	115	10
Synthetic ester	66	2

The results of the 3mm mineral oil impregnated pressboard are consistent with an experiment performed by Darveniza [10]. Darveniza measured an average pressboard dielectric strength of 3 samples, as per ASTM D149 using the step by step method and same electrode configuration, of between 22kV/mm and 23kV/mm. In this investigation the average dielectric strength of the mineral oil impregnated pressboard was 21kV/mm. Darveniza was determining the effect of aging on the dielectric strength of impregnated pressboard however does not discuss the role of the oil wedge on pressboard failure.

LIGHTNING IMPULSE BREAKDOWN VOLTAGE COMPARISON

The lightning impulse breakdown voltage was found as per ASTM D3426-97 [11]. A Haefely 10 stage impulse generator was used to provide a 1.2µs/50µs negative voltage waveshape simulating a lightning strike. Three impulses were applied at each voltage level until breakdown occurred. The voltage was raised in steps of -10kV. The same electrodes, 25mm brass cylinders, were used. Results were obtained for 1.5mm pressboard and it can be seen that ester performance is comparable to that of mineral oil. Two results for the synthetic ester impregnated pressboard were lower than the mineral oil, however it is undetermined whether this is due to the statistical nature of dielectric failure.

Breakdown was characterised by a discharge induced wear-through in the oil wedge area. Past research has indicated that the lightning impulse dielectric strengths of esters are inferior, to the extent of 15% - 20%, when compared to that of mineral oil [9]. Therefore, although the electric field across the ester may be less due to matched dielectric constants, the magnitude of the electric field required to break down the oil is lower. This may provide an explanation to why the lightning impulse breakdown voltage of pressboard impregnated in ester does not appear to be higher than that of the mineral oil. The outcome of this is that although the lightning impulse dielectric strengths of esters were identified as being lower than that of mineral oil, when an ester is used with cellulose, the permittivity matching effects may reduce the dielectric field encountered by the ester.

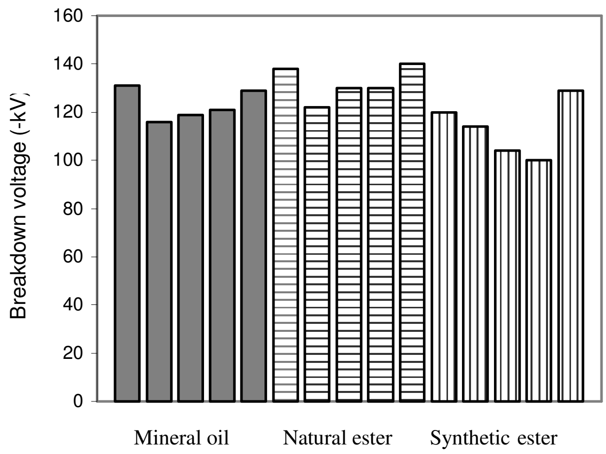

Figure 7. Lightning impulse breakdown voltage of 1.5mm impregnated pressboard

It was difficult to obtain breakdown voltage data for 3mm pressboard due to that the discharge initiated in the oil wedge tended to propagate along the surface, cause surface tracking and flash around the pressboard, even at pressboard widths of 20cm, rather than wearing through the cellulose of 3mm thickness.

CONCLUSIONS

- The ac dielectric strengths of cellulose impregnated in ester are at least equal to that of mineral oil.
- The lightning impulse dielectric strengths of cellulose impregnated in ester are comparable to that of mineral oil.
- The esters are suitable, from an impregnated cellulose dielectric strength perspective, to be used in a composite oil cellulose insulation structure.
- Further analysis is required to quantitively determine the effects of matching the dielectric constants of oil and cellulose, the effect of an oil having a higher or lower dielectric strength or the effect of oil chemistry on cellulose dielectric strength.

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