PERFORMANCE AND NEW APPLICATION OF ESTER LIQUIDS

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Abstract: The combination of solid and liquid insulation is the most utilised insulation system in high voltage apparatus, where the insulation consists of impregnated solid material and the demand on heat transfer is not negligible. The requirements on the liquid part of the insulation system are not only the electric and dielectric performance but also the performance regarding environmental requirements and dehydration capability. The use of ester liquid replacing partly or totally mineral oil is useful in order to reduce the endangering of the soil and underground water and the fire risk. The high capacity of ester liquid to pick up water can also be used for the dehydration of the paper component of the insulation system.

The contribution presents the performance of ester and mineral oil/ester mixtures concerning the electric behaviour and cover the whole range of mixture between ester and mineral oil. The dielectric parameter like loss factor and permittivity were measured for the whole mixture range in order to judge the performance of the complete insulation system regarding the compatibility of the liquid insulation with different type of papers and the loss factor of the whole apparatus. The efficiency of the hydration was checked using ester liquid as insulation or only as water carrier to fry the paper in a long or short time period.

INTRODUCTION

Because of the wide availability and low cost, petroleum-based transformer oils are probably the most widely used electrical insulating liquids in the world today - and have been for the past century [1]. Between 1930 and the mid seventies, non-flammable liquids like PCB (some trade names included Askarel, Aroclors, Pyranol, Inerteen, Chlorextol, etc.) were used for insulation purposes. During the 1970s it was determined that PCBs, in addition to having a number of beneficial properties, can be an environmental hazard and can accumulate in the environment. Also, in a fire PCBs can be chemically modified and generate high levels of dioxins. Since that time researchers in the transformer industry have tried many combinations of chemicals to remove and replace PCBs in older transformers and to find new liquids for new transformers. Transformers filled with synthetic liquids such as silicone, ester, perchlorethylene, etc. are used in special applications today. They have good dielectric and heat transfer properties but their relatively high cost and availability has limited their use to special transformer applications [1].

The paper presents results of investigations into Ester liquid and mixtures of ester with other adequate insulating liquids, recently proposed as alternatives to mineral oil [8]. One of the mostly investigated mixtures is a combination of the widely available mineral oil and a specific amount of ester liquid, which has similar electrical properties combined with fewer environmental risks but high hygroscopicity. The water saturation limit of esters is more than 40 times larger than that of mineral oils. Esters absorb water vapour from the air in larger quantities than mineral oil, and this hygroscopicity reduces the moisture content in solid insulation due to diffusion from the solid into the liquid, while the dielectric properties of ester liquids are only slightly changed. The investigations have therefore been carried out on unaged mixed liquids as well as on specimens under severe ageing conditions. Pure liquids have also been investigated to provide baseline data for comparison purposes.

MISCIBILITY OF THE LIQUIDS

The ester liquid and the mineral oil were chosen so that the colours were visually distinguishable. However, both liquids possess almost the same density [5, 6]. The mineral oil and a specific amounts of the ester liquid were poured into a vessel and slowly mixed using a stirrer. To assess the degree of miscibility, the relative permittivity and dissipation factor were determined at three different positions of the vessel for three types of mixtures. The results, presented in Figure 1, show that there is no significant difference regardless of the amount of ester added. In order to assess the temperature effect on the mixtures, the specimens were heated to 90 °C, and after few days there was no visible separation of the mixed liquids. We can, therefore, conclude that the two liquids are miscible up to 50% proportion of the ester liquid.

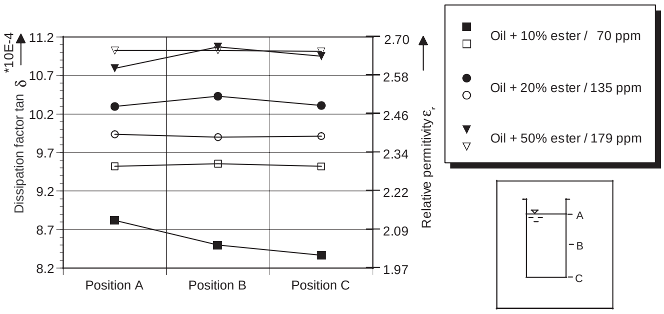

Figure 1 - Dissipation factor of different mixtures of mineral oil and ester liquids

INVESTIGATION PARAMETERS

The aim of the investigations was to determine those physical, electrical and dielectric properties, which, according to the IEC standards that are used to classify transformer oils, guarantee their quality and life. Although all the properties listed [1, 3] are important, some have a special merit for the characterisation of an insulating liquid, especially those that are likely to vary significantly with the oil purity and composition as well as with temperature and electric field. The most important properties are the electrical strength and viscosity, followed by dissipation factor (tan δ), water content and neutralisation number [3,7,9]. The permittivity, dissipation factor, and AC electric strength of both the pure and the mixed liquids and their viscosity were examined. The results were compared with the limits given in IEC and VDE standards. To simulate real working conditions as well as critical situations in transformers, the temperature was varied between 0 and 100 °C along with variations in the water content in the fluid.

The water content varied between 10 and 40 ppm for the mineral oil, between 10 and 185 ppm for the mineral oil plus 10% ester liquid, between 10 and 365 ppm for the mineral oil plus 20% ester liquid and between 10 and 1120 ppm for mineral oil plus 50% ester liquid. Only the average values at all the humidities at each temperature are shown in the figures. To determine the water content of the insulating liquids to within a total uncertainty of 5%, samples were subjected to a Karl Fischer titration test applied to oils. The results were compared with the limits given in the IEC and VDE standards. In this paper, E represents a value for the ester liquid and M a value for the mineral oil. Thus M/10/20 for example signifies a mixture of mineral oil with 10% ester liquid and a water content of 20 ppm.

Theoretical determination of the relative permittivity of the mixed liquids

A liquid mixture can be considered as two different dielectric layers where the indices 1 and 2 represent the mineral oil and ester liquid respectively, the thickness d_1 and d_2 of each depends on the percentage of each liquid. The equivalent relative permittivity of the mixture having a thickness d is given by :

$$\varepsilon_{re} = \frac{\varepsilon_{r1}\frac{d}{d_1}}{1+\frac{\varepsilon_{r1}d_2}{\varepsilon_{r2}d_1}} \qquad (1)$$

The equivalent dissipation factor of the mixed insulating liquids, treated as two different layers, is:

$$\tan\delta_e = \frac{\varepsilon_{r1}d_2\tan\delta_2 + \varepsilon_{r2}d_1\tan\delta_1}{\varepsilon_{r1}d_2 + \varepsilon_{r2}d_1} \qquad (2)$$

Table 1 summarises the calculated values of the relative permittivity and the dissipation factor of the liquid mixture according to (1) and (2) respectively. The relative permittivity, ε_{r1}, varies between 2.1 and 2.3, and ε_{r2} between 3.2 and 3.4 while the dissipation factor, tan δ_1 lies between 10^{-4} and 10^{-3} and tan δ_2 between $3x10^{-4}$ and $30x\ 10^{-4}$.

Table 1 Calculated relative permittivity and dissipation factor

Ester liquid amount (%)	0	10	20	50	100
ε_r	2.2 ±0.1	2.275 ±0.1	2.355 ±0.1	2.64 ±0.1	3.3 ±0.1
tan δ (10^{-4})	5.5 ±4.5	12.3 ±10.7	19.7 ±17.3	42.3 ±40.7	103.4 ±93.5

MEASURING RESULTS

The measurements were carried out at temperatures of 25, 60 and 90°C and at various water contents with a Schering-Bridge having a sensitivity $5x10^{-7}$ at 50 Hz.

Relative Permittivity

There is an increase in ε_r with increasing proportion of ester liquid in a mineral oil/ester liquid mixture. Such behaviour has already been observed in Table 1. There is good agreement between the experimental and theoretical results for all the liquid mixtures studied.

Dissipation factor (tan δ)

The temperature dependency of the dissipation factor of the aged and unaged specimens of mineral oil and liquid mixtures is shown in Figure 2, in which the values of tan δ are the average for all water contents at a given temperature. It can be seen that the tan δ values at all temperatures are in reasonable agreement with those obtained theoretically in Table 1.

The accelerated ageing leads to an increase in the tan δ values but they are well below the limiting value of 1 required by VDE [12] for aged oils. Furthermore it can be seen that the higher the proportion of ester liquid, the lower the ageing rate. A large amount of ester liquid mixed with mineral oil seems to have a beneficial effect on the ageing of the mineral oil mixture.

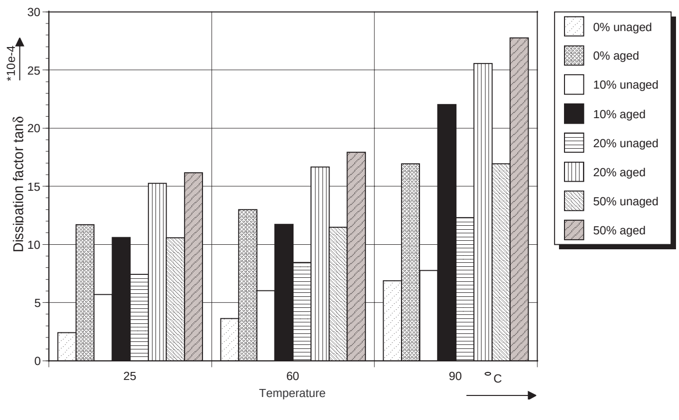

Figure 2 - Dissipation factor of new and aged ester liquid/ mineral oil -mixtures

Breakdown Voltage (U_B)

The temperature dependency of the breakdown voltages for mineral oil and liquid mixtures is shown in Figure 3. The breakdown voltages are the average for all water contents at a given temperature. The results for the aged liquid mixtures are sometimes higher than those of unaged liquids particularly for high proportions of ester liquid, for example, 50% ester liquid. Ester leads in all cases to a higher breakdown voltage at lower temperature. At higher temperature the influence of ester on the breakdown voltage is negligible.

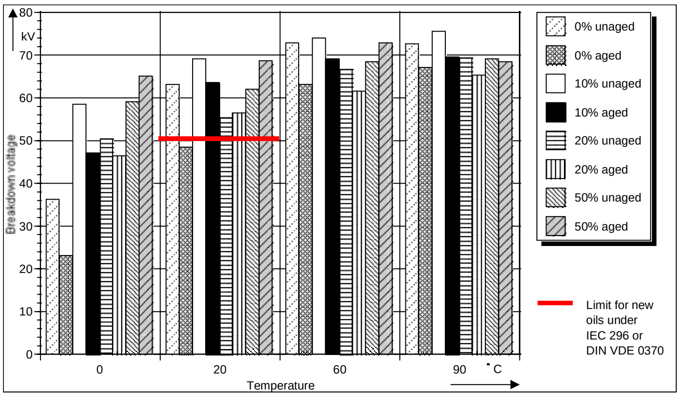

Figure 3 - Breakdown voltages of new and aged mixtures of ester liquid and mineral oil

The breakdown voltage of the mixtures is less temperature-dependent than that of the pure mineral oil. The reason is the difference in the water saturation limit. All the breakdown voltages for new and aged liquid mixtures are greater than the limit of 50 kV at 20°C required by VDE [12] for unused oils.

Relative Humidity

The relative humidity for oil is the dissolved water content of the oil relative to the maximum capacity of moisture that the oil can hold. Because the saturation-mixing ratio is a function of pressure and especially of temperature, the relative humidity reflects more than just the water content [4]. Fig. 4 shows the saturation limit of the investigated liquids.

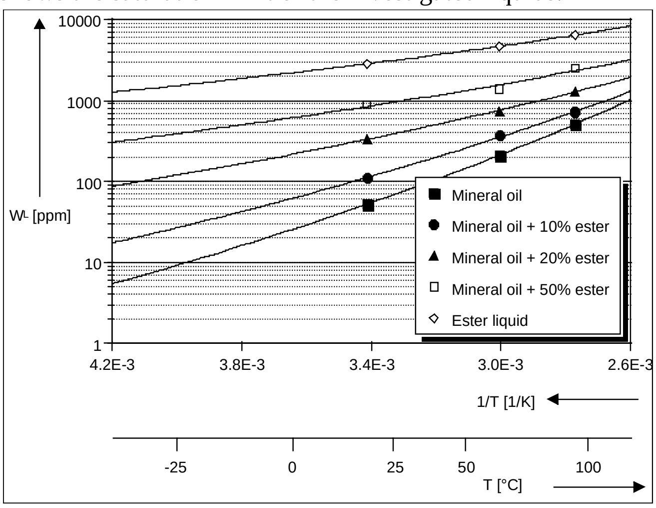

Figure 4 - Saturation limit of the pure liquids as well as for the mixtures of mineral-oil/ester liquid.

Figure 5 compares the breakdown voltage of the liquid mixtures with that of mineral oil as a function of the relative humidity. Mineral oil properties are well known to be highly temperature and water content dependent [10, 11]. The two parameters combined in the relative humidity lead to a dependency of the electric strength on this new parameter. However, the standard deviation of the data for the ester liquid is much larger than that of mineral oil, thus resulting in a smaller dependency of the U_B of the ester liquid on the temperature and actual water content and, also, on the relative water content [12].

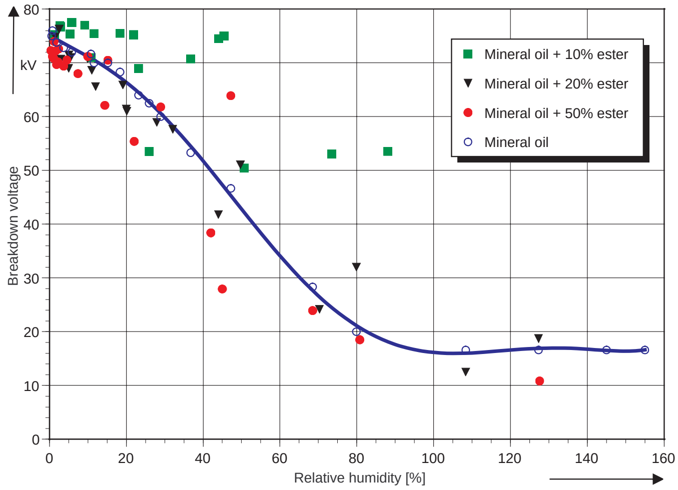

Figure 5 - Comparison of the breakdown voltage of the liquid mixtures with that of mineral oil

The dependency on relative humidity of the electric strength of the mixture containing 10% of ester is slightly better than that of the mineral oil, while the behaviour of the mixture of 20 and 50% of ester is found to be intermediate between those of the ester liquid and the mineral oil. The dielectric characteristics of aged specimens are sometimes better than those of new specimens. In order to clarify the influence of ester liquid on the ageing process, the electrical strength of aged mineral oil mixed with different amounts of new or aged ester liquid has been investigated. The results are summarised in Figure 6.

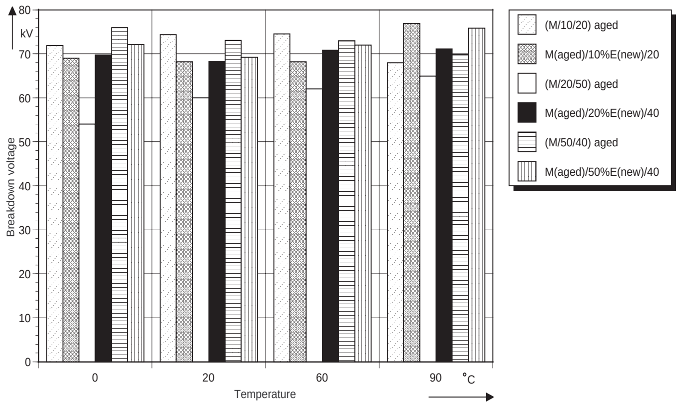

Figure 6 - Electrical strength of aged and new ester liquids / mineral oil mixtures

The ester liquid is beneficial for aged mineral oil as well as when they are both aged together. This aspect can be very helpful when retrofilling service-aged mineral oil filled transformers with liquid mixtures.

Viscosity

The viscosity of an insulating liquid is important for heat dissipation and the impregnation process. It is a principal parameter in design calculations for heat transfer by either natural convection in smaller self-cooled transformers or forced convection in larger units with pumps [1]. A low value of viscosity and a good specific heat capacity are needed to achieve a high heat transfer capability. However, high values of viscosity, such as that of ester liquids, have the advantage of quickly reaching the expected service temperature, compared to mineral oils, during a cold-restart of the transformer [11]. As viscosity decreases with the temperature, the viscosity of ester liquid at service temperature is relatively close to that of mineral oil.

Generally, the viscosity of a mixture increases with increasing molecular size and molecular weight of the constituent compounds [1]. The viscosity of mineral oil is very low compared to that of ester liquid. By mixing the two liquids, an increase in the viscosity due to the proportion of ester liquid is expected. Figure 7 shows the measured viscosity of the mixtures as well as the pure liquids at two different temperatures. As expected, the higher the proportion of ester liquid, the higher the viscosity of the mixture.

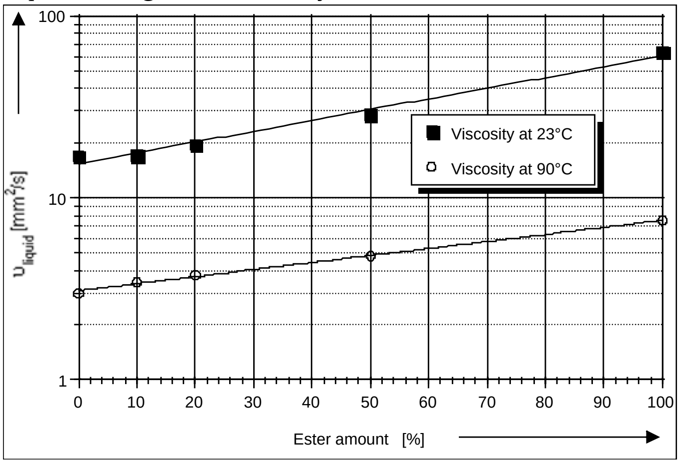

Figure 7 - Viscosity of ester liquid/mineral oil mixtures at different temperatures

CONCLUSIONS

As moisture is ’enemy number one‘ for transformer insulation, the high saturation limit of ester liquid, almost 6 times higher than that of mineral oil, reduces the moisture content in the solid insulation due to its diffusion into the liquid, and as a result, the dielectric properties of the mixed liquids are changed slightly. If necessary, excess moisture can be removed from the fluid using standard techniques. Altogether, if the transformer usually operates at very low temperatures, the application of the mineral oil and ester liquid mixtures offers increased insulation reliability. The dielectric strength at low temperatures is higher than that for pure mineral oil. Therefore, the lower risk of breakdown of the insulating liquid at low temperatures reduces the probability of a transformer malfunction.

The electrical and physical properties of the investigated mixed liquids are not inferior to those of typical transformer oils, particularly for mixtures with less than 20% ester content. For the mixture with 50% of ester liquid, the density and the cinematic viscosity exceed the limiting values suggested by the standards.

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