Performance of alternative insulating liquids at low temperature

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Abstract

Alternative insulating liquids such as ester oils can be used in transformers when ecological aspects and extra fire safety are desired. These alternative dielectric fluids have some different physical properties such as higher viscosities or much higher water solubility than mineral oil.
This contribution will show results from extensive investigations on natural and synthetic esters in comparison with one mineral oil. The AC breakdown voltage is determined for different low temperature points down to -35°C. Also different humidity levels of the oil have been investigated in order to check possible critical crystallization at very low temperature. Additionally slow natural and fast artificial defrosting of solidified natural ester is also evaluated. The results of the experiments are compared to mineral oil where possible. Finally suggestions for the safe operation of transformers at very low temperatures are presented.

1 Introduction

The interest in application of natural and synthetic ester-based fluids in different high voltage power equipment increased over the last years. Most of the parameters relevant for insulation and cooling of high voltage equipment are studied at room or normal operating temperatures. Nevertheless, this equipment has to keep its functionality over the range of various uncommon conditions. For regions with cold climate an important issue is the behaviour at low temperatures.
Bringing in operation (cold start) of the high voltage equipment filled with commonly used mineral oil at temperatures below 0°C is a consistent challenge. The procedure involves rising of the temperature from ambient to operating value. This aspect is even more important for natural ester oils which have a higher pour point than mineral oil. Information about performance of natural esters around or below pour point temperature is scarce. Authors from [1] come to the conclusion that low temperature operation and cold start is not problematic, based on investigations on a 167 kVA transformer. Recently new publications show also that dielectric performance of impregnated pressboard near and slightly below the pour point is not affected [2].
Goal of this contribution is to investigate this topic in detail, which means at different low temperatures, different moisture contents and performance evaluation depending on fast and slow defrosting.

1.1 Properties of insulating liquids under varying conditions

It is well known that even small amounts of dissolved water in transformer oil have a huge impact on dielectric strength. This fact makes oil breakdown tests in homogeneous fields a good tool to check oil quality and gives some hints about safety at operation.

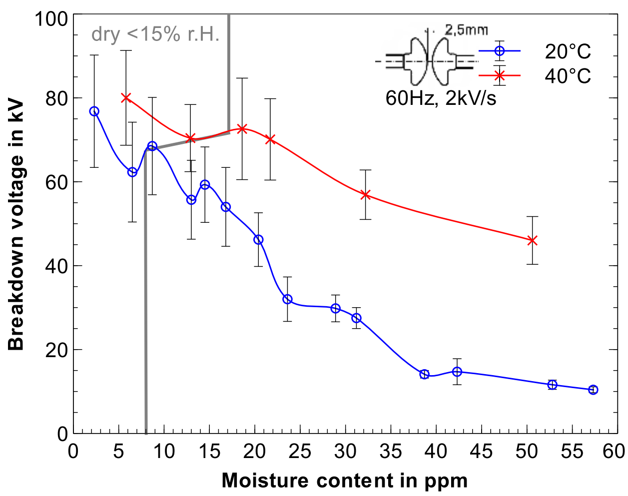

Figure 1: BDV depending on water content (mineral oil)

In figure 1 this relationship is shown. With higher temperature the water solubility rises and breakdown voltage improves although the water content in the oil stays the same. Natural and synthetic esters have similar behaviour. Due to different water solubility a comparison between different oils cannot be done on the moisture by weight scale, but based on relative humidity (see section 3.2). In literature typically investigations can be found at elevated temperature, but not at low temperature [3].

2 Experimental setup

2.1 Investigated liquids

The mainly investigated liquid is a natural ester (tri-ester based, future IEC 62770) referenced as NE. A naphthenic inhibited mineral oil (IEC 60296), referenced as MO, was chosen to compare the results. As third class of dielectric liquids a synthetic ester (IEC 61099), referenced as SE, was chosen. Table 1 shows the relevant properties of these oils for the experiments. The pour point of the natural ester (< -10°C) is significantly higher than the others. Also a big difference in water solubility can be observed.

Table 1: typical properties of three different oil classes

Typical values	**Test method**	**MO**	**NE**	**SE**
Viscosity at 40°C [mm²/s]	ISO 3104	<12	<50	<35
Pour Point [°C]	ISO 3016	< -40	< -10	< -45
Acidity[mgKOH/g]	IEC 62021	<0.01	<0.06	<0.03
Water saturation at 20°C [ppm]	Cigre n°436	55	1100	2600
Breakdown voltage (dry, 2.5mm)	IEC 60156	>70	>70	>70
Flash point [°C]	ISO 2719	>135	>250	>250

2.2 Setup and measurement system

2.2.1 Test equipment

The test equipment was an automatic oil tester to measure the oil quality by means of breakdown voltage (IEC 60156). The electrodes were calotte brass electrodes with a diameter of 36mm (VDE type) and a distance of 2mm. The reason for choosing 2mm is that with 2.5mm the limit of test equipment's voltage range can be reached (100kV, AC, 60Hz). This is especially the case for natural esters. The voltage rise was 2kV/s for all oils till breakdown occurred. Typically several measurements are performed due to the stochastic nature of breakdown. From experience the relative standard deviation is around 20% to 25%.

Moisture content is controlled by coulometric Karl-Fischer titration (IEC 60814). For high water contents the absolute accuracy and relative standard deviation (RSD) are 1% (for 100ppm). At lower moisture contents for mineral oil the RSD rises. In best case 20% can be obtained, which for example for oil with 5ppm water content translates to 5 +/- 1ppm.

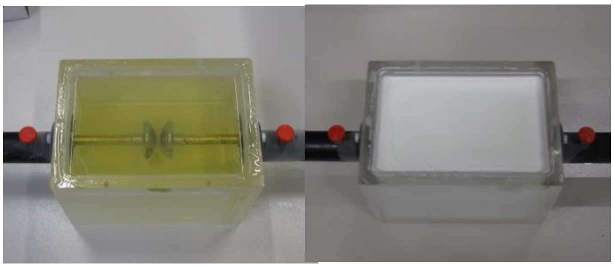

Figure 2: SE gel-like (left) and NE solid (right) at -35°C

2.2.2 Test cell, test preparations and test procedure

The test cell is made from transparent polyacryl (PMMA) and has a volume of around 1.5 litres. Inside there are two VDE electrodes mounted with adjustable distance. The cell has a lid with a gasket in order to reduce moisture diffusion to or from the atmosphere. Several test cells were manufactured in a way they can fit onto the automatic oil tester. Before testing, the oil filled cells were placed in a vacuum chamber in order to remove any gas bubbles that could be captured within the oil. For low temperature measurements the test cells were put inside a cooling chamber. Around 10 hours are needed to reach thermal equilibrium. To be on the safe side the cells were cooled at least 15 hours.

It is also important to adjust the correct gap distance, because the test cell material changes its dimensions because of thermal contraction. The electrode gap at ambient temperature was adjusted in such a way that after contraction to the desired temperature a distance of 2mm was obtained. Mineral oil was in liquid state for all temperatures. Synthetic ester developed a gel like state at -35°C, like natural ester at -25°C. In case of NE, where the oil was solidified at -35°C, it was only possible to measure one breakdown. Indeed, the resulting gases couldn't be removed and the next breakdown wouldn't be statistically independent. So each time the oil was changed and cooled down to the desired temperature. The following results are mean values of 10 to 20 breakdown voltages.

3 Results

3.1 Comparison of different oils

The first test shows temperature dependent breakdown strength of dry oils. Mineral oil had a water content of 4.5ppm, natural ester 45ppm and synthetic ester 110ppm. It means that each sample is below 10% of saturation at room temperature.

At room temperature, breakdown voltages are equivalent for each oil. Breakdown strength of mineral oil decreases with lower temperature. Synthetic ester seems to behave

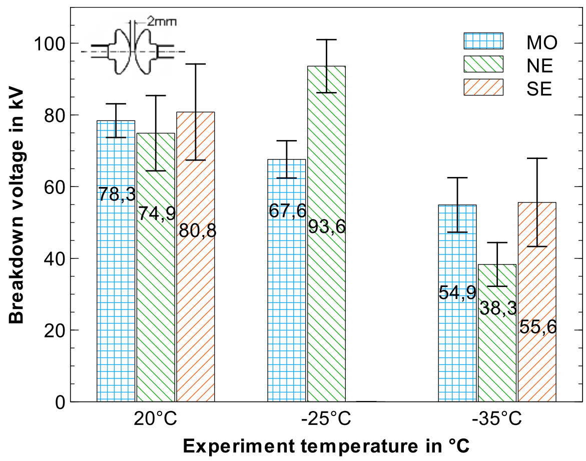

Figure 3: breakdown voltage of dry oil with 2mm gap

similar, but data for -25°C is unavailable. The natural ester behaviour is different. It is in a solidified state and till -25°C the dielectric strength improves. After a certain point it is reduced by a large value. It is still acceptable, but the reason is not certain. To investigate this phenomenon further, water content of the oils was varied.

3.2 Water influence at low temperature

Oil samples were prepared with three different moisture contents. This moisture content should represent dry, medium wet and very moist condition. Because the oils have different water solubility, it makes no sense to try to have same ppm (µg water per gram oil) values, but to prepare the samples to same relative humidity at room temperature. It was defined that these values should be around 5%, 15% and 25% relative humidity. The resulting moisture contents by weight are shown in table 2.

Table 2: moisture content of investigated oil samples

	MO	NE
Dry	4.5 ppm	45ppm
Medium	8.5 ppm	180 ppm
Wet	14.5 ppm	300 ppm

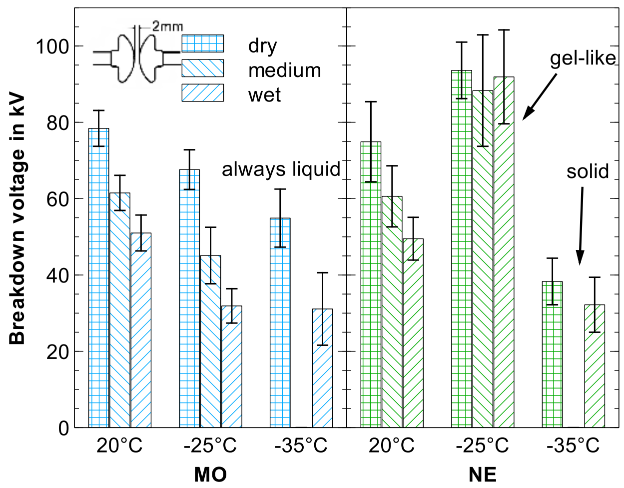

Figure 4: BDV depending on water content and low temperature

For mineral oil the trend is very clear. With both lower temperature and higher water content the dielectric strength is reduced. This is a good indication that relative humidity and breakdown voltage correlate even at low temperature. Natural ester has at 20°C the expected behaviour, but at -25°C the BDV is very high. This is independent from water content. Again like in the previous section, at -35°C the breakdown strength drops.

It seems that water content isn't a significant factor for this effect. Between -25°C and -35°C it is not clear if this effect happens gradually or if the drop is sharp. Therefore the next series of investigations with a more detailed temperature resolution were conducted.

3.3 Detailed investigations with NE

The following experiments were all done with NE in dry condition with 45 to 50ppm water content. The temperature increments were reduced to 5 Kelvin. Like the other tests all values are mean values of at least 10 measurements with oil change after each breakdown and cooling down from ambient to the desired temperature.

Figure 5 shows that the natural ester gets better dielectric strength when it changes its aggregate state from liquid to gel-like. This process stops at -25°C when the oil becomes solid. At -30°C the mean value is reduced, but it should be noted that the standard deviation is very large. With the existing data it cannot be recognized if the decreasing strength is linear or not. Still the value of 81.3kV is excellent, bearing in mind that the oil gap is just 2mm.

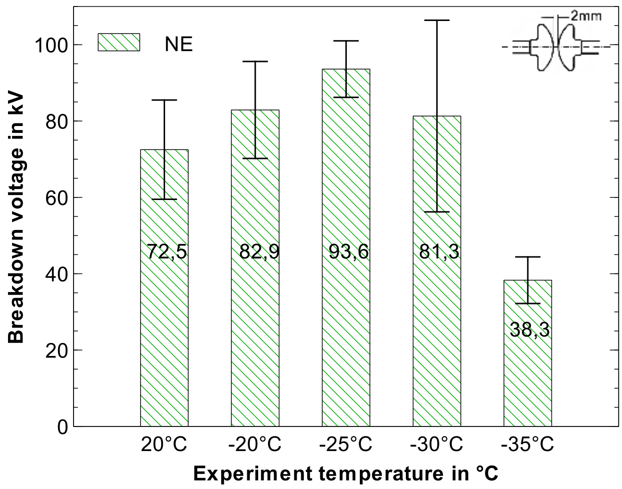

Figure 5: Breakdown voltage of dried NE with 2mm gap

3.4 Regaining of electric strength

In the introduction it was mentioned that the cold start is a critical situation. Goal of the next experiment was to see, if NE at -35°C with the reduced strength would recover to its former performance, if the temperature rises. This experiment is quite challenging, because water condenses on the test cell and moisture ingress or other condensation nuclei are affecting the breakdown values. Also produced gases from the breakdown cannot dissolve and the following measurement is invalid.

Despite these issues, breakdown voltage was measured during warming up of the test cell and oil. Of course the BDV values, which were measured below pour point are much too low due to the gas discharge. But after several hours warming up to ambient temperature, the values improve almost to the original state. They are slightly lower because water ingress couldn't be avoided completely.

A solution in order to give these measurements a qualitative meaning is to compare natural ester NE to mineral oil MO. The results can be seen in figure 6 and the natural ester has the same performance as mineral oil.

Figure 6 shows actually results of two experiments, namely slow and fast defrosting. The motivation behind these two experiments is to check, if a cold start under significant load or a careful warming up would affect the results.

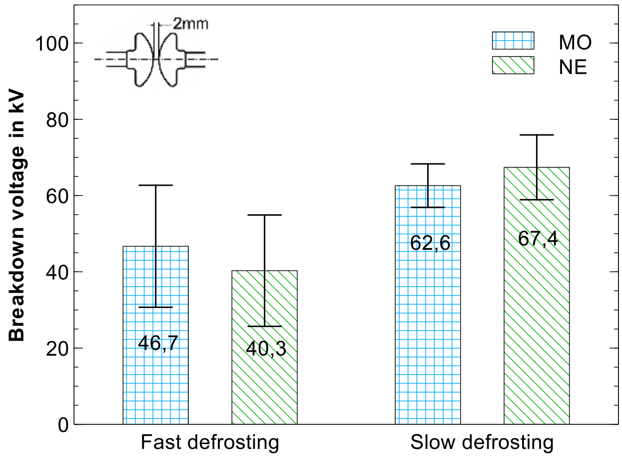

Figure 6: BDV after warming up from -35°C to ambient with dry natural ester

The fast defrosting was achieved in a heating chamber in just two hours at 65°C (around 30 K/h). The natural defrosting was achieved by leaving oil samples at room temperature (<10 K/h). The fast defrosting values look worse than the natural defrosting. During that procedure small water bubbles have been observed between the electrodes. A reason could be that the water couldn't be dissolved fast enough, when the oil came to the liquid state and thus was saturated. After an additional waiting time (ca. 3 hours) the dielectric strength was regained. It is important to stress that natural ester has almost the same performance as mineral oil.

4 Conclusion

This contribution showed results comparing breakdown voltage of different classes of insulating liquids at low temperature. It can be concluded that the breakdown strength of natural ester NE for homogenous electrical field is highly dependent on temperature. When the temperature (-25°C) is below the pour point, the oil is not solidified, but in very thick aggregate state. At this temperature breakdown voltage of NE is still very high, even higher than at room temperature. As soon as NE oil gets solidified (-35°C) its insulation strength drops from 72 kV (room temperature) to 38 kV (-35°C). It should be remembered that these values are obtained for 2 mm electrode distance. For the standard distance of 2.5 mm the values would be higher and would reach the highest acceptance limits from standards.

Moisture content has a high influence on both oils at room temperature. As expected, an increase of oil humidity reduces its dielectric strength. At low temperature, insulation strength of mineral oil (liquid state) is still very dependent on moisture. On the opposite, insulation strength of natural ester oil at low temperature (gel-like or solid state) is not dependent on water content.

After both slow and fast defrosting, the natural ester has the same performance as mineral oil. Nevertheless, it can be underlined that investigated oils regain a better dielectric strength after slow defrosting.

Finally, it can be concluded that the natural ester has excellent properties regarding dielectric strength down to -30°C. At lower temperature the breakdown voltage is reduced, but the values are still good.

5 References

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