Ester Fluids As Alternative for Mineral Based Transformer Oil

H. Boris, E. Gockenbach, B. Dolata
Institute of Electric Power Systems
High Voltage Engineering Section, Schering-Institute
Leibniz Universität Hannover
Callinstr. 25A, 30167 Germany
dolata@si.uni-hannover.de

Abstract- One of the key component of electrical power distribution networks is transformers, interconnecting between transmission and distribution voltage level or between different networks. Cooling affords a liquid immersed insulation for high power use, thus the insulation of these devices usually consists of mineral oil and cellulose based porous material immersed therewith. Synthetic ester fluids as well as natural based ester fluids will be presented in this article. The electrical and dielectrical properties and the measurements procedures will be described.

I. INTRODUCTION

As mineral insulating oils which are one of the key component of the insulation comprise several risks concerning aging, fire resistance and ecology, the use of ester liquids become increasingly attractive. Moreover, the price of mineral oil based products has been continuously escalating. In this contribution new ester insulating liquids are introduced that combine the advantages of mineral insulating oils and ecological friendly, low viscosity synthetic ester liquids.

Insulating liquids of mostly synthetic origin like High Molecular Weight Hydrocarbons or Silicone Oils could not so far substitute mineral oils as their application characteristics are inferior or their price is disproportionate. In Europe only synthetic ester liquids, named Midel 7131, have proven their advantageousness for transformers regarding environmental and aging aspects.

The developed ester liquids meet the major and important conditions for new insulating liquids that are environmental friendliness, high fire resistance and lower viscosity. Therefore, they are very promising liquids for use as cooling and insulation liquid in transformers and another high voltage apparatuses.

This contribution presents some experiments on the electrical and dielectric characteristics of these liquids, which have been performed to approve their usability for transformers.

Mainly the Breakdown Voltage ($U_{bd}$), the Dielectric Dissipation Factor (tan $\delta$), the Relative Permittivity ($\varepsilon_r$) and the Partial Discharge Inception Voltage ($U_{PDIV}$) characterize an insulating liquid and are required for a qualified dimensioning of a transformer.

II. MINERAL INSULATING OIL

Because of the wide availability and the cost benefit that result from this kinship, 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]. Indeed, for most of high voltage transformers, the main insulation is a combination of mineral oil with cellulose materials.

Mineral insulating oils consist of different hydrocarbons, namely Paraffines, Olefines, Napthenes and Aromates. These hydrocarbons are constituted of carbon and hydrogen linked with mono and double bonds. Depending on the kind of bonding the aging stability of the molecule is also inconsistent. Due to stresses like pyrolysis (temperature), hydrolysis (water) and the electrical field the bonds are prone to cracking and therefore leading to different dissolved gases that are used for Dissolved Gas Analysis (DGA). Catalysis from the metals in the transformer additionally facilitates this process.

Although this the use of mineral oils in power transformers has proven to be very reliable it also comprises several disadvantages. Besides the aging also the environmental endangerment resulting out of a transformer spillage has to be kept in mind.

III. ESTER FLUIDS

An alternative to the mineral oils are ester liquids consisting of naturally or synthetically arranged constituents. Basically esters can be classified in five groups:

- Monoesters
- Dicarboxylic esters (Diesters)
- Glycerinesters
- Polyolesters
- Complexesters

All kinds of esters have to be synthesized out of an acid and an alcohol. Only Polyol- and Complexesters are adequate for high stress conditions that it is required for use in a high voltage transformer. These ester groups are the strongest basestock among synthetic oils. The competence is originating from the absence of secondary hydroxyl groups and a
quaternary carbon in the $\beta$-position. Typical alcohols used for synthesis are neopentyglycol, trimethylol-propane, pentaerythritol or dipentaerythritol. The viscosity of the product can mainly be controlled in the group of Complexesters which are polyols esterified with a blend of mono-, bi- or tri-functional carbonic acids to form oligomer molecules with a selectable sheer stability [3].

The new liquids have been designed for power transformer use out of this “construction kit” and are the center of a whole family of esters fitted for every kind of transformer application (distribution, network, traction and machine transformers).

<table>
<thead>
<tr>
<th></th>
<th>Midel 7131</th>
<th>s-Ester</th>
<th>n-Ester 1</th>
<th>n-Ester 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>tan $\delta$ (%) at 20°C</td>
<td>0,001</td>
<td>0,0006</td>
<td>0,001</td>
<td>0,003</td>
</tr>
<tr>
<td>tan $\delta$ (%) at 90°C</td>
<td>&lt;0,03</td>
<td>&lt;0,03</td>
<td>0,009</td>
<td>0,005</td>
</tr>
<tr>
<td>$\varepsilon_r$ at 20°C</td>
<td>3,3</td>
<td>3,0</td>
<td>3,0</td>
<td>3,0</td>
</tr>
<tr>
<td>Breakdown voltage (kV)</td>
<td>&lt;75</td>
<td>99</td>
<td>&lt;75</td>
<td>56</td>
</tr>
<tr>
<td>Fire point (°C)</td>
<td>322</td>
<td>303</td>
<td>356</td>
<td>360</td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>-60</td>
<td>-50</td>
<td>-31</td>
<td>-21</td>
</tr>
<tr>
<td>Kinematical viscosity (mm²/s) at 40°C</td>
<td>28</td>
<td>25</td>
<td>37</td>
<td>33</td>
</tr>
</tbody>
</table>

Table I shows the technical specifications of producer. The letter $s$- symbolizes synthetic and $n$- natural ester fluid.

IV. MEASUREMENT PROCEDURES

Breakdown Voltage

For the measurement of the Breakdown Voltage versus temperature according to IEC 60156 [4] a test vessel has been used as depicted by Fig. 1.

The temperature have been chosen to simulate ambient 20°C, operating 50°C as well as the temperature at overload 90°C and Hot Spot temperature 110°C. The cylindrical shell around the electrodes allowed a heating of the test setup up to 110°C by use of a thermostatic heater. For the measurement a rise of the voltage of 2 kV/s and the electrode gap of 2.5 mm has been chosen.

Partial Discharge Inception Voltage

For the determination of the Partial Discharge Inception Voltage ($U_{PIV}$) according to IEC 61294 [5] a test vessel with a needle-sphere and needle-plate electrode arrangement has been used. The measurements occurred at 20°C. The test voltage rises of 1 kV/s up to the occurrence of stationary partial discharges with $q_s \geq 100$ pC. The test vessels are depicted in Fig. 2.

Dielectric Dissipation Factor $\tan\delta$ and Relative Permittivity $\varepsilon_r$

The Dielectric Dissipation Factor $\tan\delta$ and the Relative Permittivity $\varepsilon_r$ are measured with a CPC 100 Multifunction Primary Test System and a CP TDI Tangent Delta system manufactured by OMICRON. For these investigations the temperatures 20°C and 90°C have been used. The electrodes arrangements are depicted in Fig. 3.

As known from theory and scientific experience, the repeatability and accuracy of measurements play a very important role to reach comparability of the results. For this reason, the same measurement condition and handling of investigated samples was also necessary.

In order to meet the conditions for each investigated samples the test vessels have been cleaned and the electrodes polished. For the electrically and dielectric measurements the investigated ester fluids have been tested in delivered, not prepared condition. The water content occurred 60 ppm-70 ppm.
V. RESULTS

A. Breakdown Voltage

The Breakdown Voltage has been determined and depicted as average value in kV. The standard deviation from six measurements has been calculated. The Fig. 4 shows the Breakdown Voltage in dependence on the temperature in the range from 20°C to 110°C.

Fig. 4. Breakdown Voltage for different ester liquids versus temperature

For the synthetic based ester liquids the standard IEC 61099[2] is valid. For this kind of pentaerythrit esters the limit of the Breakdown Voltage of 45kV is required [9]. On the other hand the definition of IEC standard for natural based ester liquids is still in progress. For all types of ester liquid is to observe that the Breakdown Voltage is about 50-60 kV at the operating temperature of 50°C as well as the Hot Spot temperature of 110°C. The average value of all the investigated ester liquid is higher as 45kV and accomplishes the standard IEC 61099.

B. Partial Discharge Inception Voltage

The investigations for the determination of the Partial Discharge Inception Voltage have been analyzed for two different electrode arrangements. The needle-sphere and needle-plate have been used to simulate different operation conditions. Fig. 5 shows the Partial Discharge Inception Voltage and the standard deviation in kV. The stationary partial discharges with \( q_s \geq 100 \, \text{pC} \) are occurred up to 22,5-27,5 kV for the needle-sphere electrode and up to 27,5-32,5 kV for the needle-plate electrode arrangement. As a result it can be easily seen, that the natural based ester liquids have a good and comparable characteristic to synthetic ester fluids.

C. Dielectric Dissipation Factor \( \tan \delta \)

Fig. 6 shows the results of Dielectric Dissipation Factor \( \tan \delta \) in dependence on the temperature. The ambient 20°C and Hot Spot 90°C temperature has been used. It can be seen that dielectric losses of investigated ester liquids are comparable. Only synthetic ester liquid named s-Ester shows particular variations. As dielectric losses only marginally contribute to transformer heating due to losses this aspect is of minor importance for transformer operation.

D. Relative Permittivity \( \varepsilon_r \)

Fig. 7 shows the Relative Permittivity \( \varepsilon_r \) in dependence on the temperature. The ambient 20°C and Hot Spot 90°C temperature has been used. It can be seen that dielectric losses of investigated ester liquids are comparable.

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When looking at the relative permittivity as it is depicted in Fig. 7 it can be seen, that the measured values are comparable between the ester liquids. The relative permittivity of about $3.0 \pm 0.5$ is an advantage for the design of the insulation as the homogeneity of the electrical field at the interface between cellulose ($\varepsilon_r=5.6$) and ester fluids ($\varepsilon_r=3.0$).

**E. Water Saturation Point**

The water saturation point based on exponentially correlation has been calculated. Fig. 8 shows the different saturation point were $w_0$ and $H$ are oil specific coefficients.

![Diagram showing water saturation point for different ester fluids](image)

**Fig. 8. Water saturation point for different ester fluids**

VI. CONCLUSION

The presented experiments have shown that ester liquids are an alternative to mineral insulating oils for use as insulating and cooling system in transformers. As with continuously increasing price of mineral based products also the naturally based esters become more attractive.

The Breakdown Voltage about 50-60 kV fulfilled the standard IEC 61099 requirements. The investigations of Partial Discharge Inception Voltage have shown that the natural based ester liquids have a good and comparable characteristic to synthetic ester fluids.

The relative permittivity of all investigated esters is comparable (3.0) and is an advantage in designing an insulation. The high saturation point as the case may be the high water uptake capabilities of ester liquids can bee used by retrofilling old transformers.

Ongoing experiments concerning aging and gassing behaviour (DGA) will examine all remaining aspects valuable for operation of ester liquids in all kind of transformers. Further investigations e.g. on the gassing behavior are necessary to complete the evaluation of the new ester liquids. Additional tests of the breakdown behavior at large gaps will show the usability of the new ester liquids for high voltage applications in power transformers.

REFERENCES