Physico-Chemical Properties of Power Transformer Oil Mixtures

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Abstract—This work is devoted to the study of the physico-chemical properties (aspect, colour, density, water content, acidity, discharge voltage, dissipation factor, viscosity and flash point) of mixtures between a used transformer mineral oil and a new one other of the same nature, and compatibles between them for all ratios. It is oriented towards the research of optimal ratios enabling to have acceptable properties of the mixture.

I. INTRODUCTION

Electrical energy transmission and distribution systems are essentially constituted by power transformers that consists one of the most expensive elements. It is therefore necessary that they operate correctly during many years. Most of power transformers through the world are filled with insulating liquids. Thanks to their good thermal properties, these liquids permit to ensure the electric insulation as well as the transfer of heat [1]. Mineral oils are the most used in power transformers, on one hand for their physico-chemical properties and on the other hand for their low cost in spite of their weak resistance to fire.

Nowadays, most of power transformers exceed the 25-30 years [2-4]. Their replacement by new ones, simply because of their age, is not economic and implicates a certain number of technical constraints. The re-replenishment is a solution often considered but it always remains 10% of the old liquid in the windings and the walls of the tank after emptying [5]. Moreover, leaks of oil through the tank require sometimes adding of available oils which are not the same than those of origin.

The aim of this work is to find good ratios ensuring acceptable characteristics for mixtures between a used old oil and an new one other of the same nature. For that purpose, two napthenic oils are considered, the Nynas Nytro 10 GBXS of 15 years old and a new Borak 22.

This survey deals with the study of the main characteristics that are required for transformer oils, i.e. those related to the physico-chemical, electrical and thermal properties. A comparative survey has been led on the two oils of basis, and afterwards on the different mixtures. This survey is inspired by economic and technological considerations. The main goal is to find mixture proportions permitting to get acceptable performances with lower cost.

II. EXPERIMENTAL TECHNIQUES

The oil of basis is not inhibited, i.e. it doesn't contain any additives for oxidation limiting effect. It has been removed from a substation transformer after 15 years of service, for countenance of excessive rates of carbons. The second oil (BORAK22 type), new and with clear color, is naphthenic too. Eleven samples have been thus achieved. The two extremes concern the two oils separately. And the nine others correspond to ratios of mixture of Borak in the Nynas, from 10 to 90% (table 1).

For this survey, a series of tests is achieved in order to characterize the two types of oil separately in a first time, and their mixtures afterwards. It enables us to estimate the physico-chemical, electrical and thermal properties of each type of oil. The studied parameters are as follows:

- Physico-chemical properties (aspect and color, density, water content and acidity)
- Electrical properties (discharge voltage and dielectric losses)
- Thermal properties (viscosity and flash point)

In order to have an homogeneous mixture and a representative analysis, it is necessary to mix the two oils with the help of a magnetic agitator at constant speed of 500 rpm (turns per minute) during 40 minutes.

The tests have been achieved under the following atmospheric conditions:

- Ambient temperature average of 22 °C.
- Average humidity in the laboratory: 46%.
- Atmospheric pressure of 1 bar.

III. PHYSICO-CHEMICAL PROPERTIES

A. Aspect and Color

The oil color and its aspect are very important visual characteristics for the oil analysis. This test is achieved thanks to a colorimeter according to ASTMD 1500 standard. Figure
presents the different measured values of color for the prepared mixtures. They present little variations and reach a maximal value equal to 1 that is below the limit fixed by standards. The color number of Borak22 and samples 6 to 9 is lower than 0.5, corresponding to the limit of the measurement equipment.

### TABLE 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Composition (%)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>10% B, 90% N</td>
</tr>
<tr>
<td>2</td>
<td>20% B, 80% N</td>
</tr>
<tr>
<td>3</td>
<td>30% B, 70% N</td>
</tr>
<tr>
<td>4</td>
<td>40% B, 60% N</td>
</tr>
<tr>
<td>5</td>
<td>50% B, 50% N</td>
</tr>
<tr>
<td>6</td>
<td>60% B, 40% N</td>
</tr>
<tr>
<td>7</td>
<td>70% B, 30% N</td>
</tr>
<tr>
<td>8</td>
<td>80% B, 20% N</td>
</tr>
<tr>
<td>9</td>
<td>90% B, 10% N</td>
</tr>
</tbody>
</table>

The density is measured according to NFT 20-050 standard (limit value <0.91) by using a test-tube, a densimeter and a thermometer. The density of the two oils of basis and constituted mixtures varies weakly from the fact that the oils are of the same class presenting a good miscibility. Figure 2 presents the density variations. One can note also that the densities of the different mixtures are relatively nearer the ones from the others and, all mixtures present densities lower than the tolerated limit. The Nynas density is however greater than the one of Borak22. This is due, in part, to the presence of water and also of particles in this oil.

### C. Water content

Water content (moisture) is a primordial data for insulating oils characterization. It is therefore important to measure it directly after the mixing of each sample without resting in order to take the most representative value. The measurements are performed according to IEC 60814 standard, while respecting what follows:

- Getting three measurements on samples removed from different places of the bottle because of the possible non homogeneity of the solution.
- The measured water content in ppm (mg/kg) is the arithmetic mean of the three tests values. The limit values (<20 ppm for P=260MW and <30 ppm for 37MW).

The variations of water content in the different samples are of great importance from the fact that the two oils of basis contain, in their origin, very different quantities of moisture. Borak 22 contains 10 ppm, that are in the limits of the most severe standards, and the Nynas which contains 50 ppm, the value even overtaking the limit of water miscibility in this oil (45 ppm). Figure 3 presents the variations of water content which values are elevated, nearly over what is tolerated by standards. We notice that, for the most unfavorable mixture (10% Borak/90% Nynas), the water content is greater than the one of the lonely Nynas. For the mixture 90% Borak/10% Nynas, water content passed all the same to a value of 35 ppm.

Water content doesn't affect the liquid strength so much that it doesn't overtake 50% of its saturation limit (solubility) [1]. If one considers that the saturation of water at ambient conditions...
Temperature (20 °C) is of about 45 ppm for naphthenic mineral oils [1, 6], the dielectric strength should decrease for water contents greater than 22 ppm. On the other hand, the oil resistance is affected by water contents superior to the solubility, i.e. 45 ppm [1]. It is also necessary to note that the solubility depends highly on temperature (it reaches 100 ppm for T=40°C) and on the nature of the liquid (it overtakes 1000 ppm for tetraester at 20°C).

We can reassemble the remarks concerning the influence of water content as follows:

- The variation of water content doesn’t follow the mixture composition.
- The limit value (20 ppm) is often overtaken and in certain cases, the measured values are different between two successive tests.
- Removal and storage conditions can have a great influence on water content, as much more that humidity of the laboratory is not constant and can thus influence on the measurement.
- The Nynas is old insulating oil that began to oxidize and present a level of water saturation more elevated than the one of Borak22 which is new oil.
- It is sufficient to add 10% of Nynas to the Borak 22 so that the water content in the mixture overtakes the limit fixed by standards.

**D. Acidity**

The acidity number Ia is calculated according to NF T 60-112 standard (limit value <0.5). Figure 4 presents the variations of acidity as a function of the rates of mixture. It is more elevated in the alone Nynas, from the fact of its age. The measured values are however below the limits fixed by standards.

Note also that all mixtures present an acidity number included between those of the basis oils. Elevated values indicate a beginning of oxidization. Moreover, as the acidity increases the solubility of water in oil, this can degrade the paper (cellulose).

**IV. ELECTRIC PROPERTIES**

**A. Discharge voltage**

The measurement of discharge voltage is achieved thanks to a numerical spintometer in accordance with the specifications of IEC 156 standard. It is also important that the temperature of oil during all the test operation doesn't differ from the ambient temperature in the laboratory by ± 5°C. The result is calculated by the average of six tests, due to the weak repeatability of each test series.

The dielectric strength Ds is calculated from the following relation: \( Ds = 4.5 \times Tc + 5 \), where \( Tc \) is the discharge voltage. Generally, the discharge voltage trends to improve progressively as the proportion of Borak 22 increases. It varies between 14.2 (for mixture 9) and 58.71 kV/cm (Borak22 alone). What is unexpected is the strength of the alone Nynas which is clearly better than the mixtures one, even at weak
proportions with 10% of this latter. Figure 5 presents the variations of discharge voltage for different ratios of mixture. One will point out that all mixtures present lower strengths than those of the two oils of origin.

According to EN 60156 standard, a dielectric strength between 10 and 30 kV is insufficient (case of all mixtures). Between 30 and 50 kV, it is passable (case of the Nynas). It is good and acceptable between 50 and 70 kV (case of Borak22). A weak strength indicates the presence of water and particles in oil.

B. Dielectric Losses

The measurement of dielectric losses (dissipation factor, permittivity and resistivity) is of great importance. It informs us on the ability of the mixtures to perform their first role (the electric insulation). This analysis is achieved thanks to an automatic apparatus (BAUR DTL) according to IEC 247 standard.

1) Dissipation factor ($\tan \delta$): Figure 6 presents the variations of $\tan \delta$ according to the ratio of Borak 22 in the Nynas. Generally, the dissipation factor ($\tan \delta$) decreases with the increase of the Borak ratio in the mixture. It is one of the parameters that interpret best the mixture process. It varies by decreasing when more important proportions of Borak 22 are added to the Nynas.

All mixtures present losses included between those of Borak22 and Nynas. The value of $\tan \delta$ is 0.0057 for Borak22 (close to the one mentioned on its technical card) and 0.0291 for the Nynas. It appears that the Nynas value (15 years old) is more elevated than the one of Borak22 (new). This is logical because $\tan \delta$ is very sensitive to ageing products. However, the limit value has not been overtaken (<0.05).

2) Electric resistivity ($\rho$): Resistivity shows enough expected variations (figure 7); it increases progressively than Borak 22 is added to the Nynas, with a minimum of 10 GΩm for the only Nynas. However, from these results, it appears that a mixture of 90% Borak/10% Nynas would even improve the oil resistivity.

The resistivity is one property greatly dependent on the oil conditioning and can be influenced by the presence of outer particles as impurities that should be in great number in the Nynas. It increases as the ratio of Borak in the mixture is increased. Thus, the resistivity of Borak22 (new) is better than the one of the Nynas (used). The mean values varies between 10.89 GΩm for the Nynas and 53.83 GΩm for mixture 9.

Moreover, the presence of an insoluble aqueous phase in oil decreases the resistivity (case of the first mixtures with elevated water content). Similarly to the dissipation factor, this characteristic is very sensitive to contaminants and ageing products (this is noticeable on the Nynas which is in service since 15 years).

3) Dielectric Permittivity ($\varepsilon_r$): All mixtures, including the oils of basis, have a relative permittivity varying between 2.19 and 2.23 ($\varepsilon_r$ is nearly constant) (figure 8). The limits (1.5 < $\varepsilon_r$< 2.5) have not been overtaken.
The permittivity is an intrinsic characteristic, it essentially depends on the oil chemical structure (it characterizes the polarity of molecules). More the permittivity of the medium is weak, more this latter can endure the most elevated electric constraints (This is valid for all mixtures, particularly mixture 9).

V. THERMAL PROPERTIES

As the same with the physico-chemical or electric properties, those linked to heat transfer are of great importance. The analyses that follow will enable us to conclude if the oils of basis as well as their mixtures are able to play their second role, i.e. the heat evacuation. For instance, two tests are achieved: the kinematic Viscosity and the flash point.

A. Cinematic Viscosity

The viscosity measurement has been performed by the means of a viscosimeter according to ASTM D 445 standard. At 40°C, the viscosity varies between 9.8 for the Nynas and 10.9 for Borak22, and at 100°C, it varies between 2.4 for the Nynas and 2.6 for mixture 3 (figure 9).

The Nynas oil has a faintly better viscosity than the one of Borak22 at low and high temperatures. However, all mixtures present relatively good viscosity whatever is the temperature. Heat transfer is not therefore affected by the Nynas deterioration. Figure 10 shows the variations of the viscosity number. It varies between 3.9 for mixture 3 and 4.4 for mixture 8. This indicates that these two mixtures present the best thermal characteristics, because the oil is as much better than its viscosity variation according to temperature is weak, even though, in a general way, all mixtures (including Borak22 and the Nynas) have a good viscosity number.

B. Flash Point

The flash point is determined with the help of a Petrotest device according to ASTM D93 standard. It varies from 143 to 156°C (mixture 3) and the Borak22 one is more elevated than the Nynas one (figure 11). However, all mixtures present acceptable flash points, greater than the standards fixed limit (>130). One notices that the evolution is somewhat uncertain and doesn't obey to any logic with regard to the mixture composition. It depends on the light part of oil and is extremely sensible to contaminants resulting from more volatile products as gasoil or gasoline (case of the Nynas oil which is 15 years old and that present an elevated rate of impurities).

VI. CONCLUSION

Although the two oils are of the same nature, not presenting therefore any problem of compatibility or miscibility, the obtained results on the oils, alone or mixed proved out to be, for most characteristics, different from a
proportion to the other. It is particularly owed to the different ageing, but also to the water content which is very different in the two oils. The variations of the different parameters don't follow a linear relation with regard to water content in each mixture. This indicates that several parameters interact simultaneously to determine the behavior of a given mixture. Other complementary experiments are necessary to separate especially the effects of the nature of the liquid of basis and water content.

The parameters that show a clear change as a consequence of the mixtures between the two oils of basis are: water content, resistivity, dissipation factor and discharge voltage. Indeed, one notes a well correlation between water content and discharge voltage. It makes these two parameters the most favored in surveys specific to power transformers insulation. The Nynas properties are improved by the addition of Borak 22 and are led to values acceptable by standards, except the discharge voltage that seems to not be improved by all proportions of mixture, whereas the one of the Borak 22 is nearly double of the Nynas one. This can be attributed to the fact that the achieved mixtures are not sufficiently homogeneous, well that water content in these mixtures seems to be restored to acceptable values for ratios upper than 50/50%.

Several properties of oil are not severely affected by the most unfavorable oil mixtures, like the acidity, color, permittivity, viscosity and flash point.

REFERENCES