Temperature Effect on Dielectric and AC Breakdown Properties of the Cellulose Insulation Paper Immersed in Mineral-Palm Oil Mixture

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Abstract. Mixed oil is considered as an ideal insulating fluid for its great physicochemical and insulation properties. A novel mixed oil consisted of 75 vol.% mineral oil and 25 vol.% palm oil, was developed by our team and its main properties basically come up the standards of IEC 60296:2012. In this study, the dielectric properties of mineral oil-impregnated paper (MIN-IP) and mixed oil-impregnated paper (MIX-IP), were comparative analyzed at 25 °C-65 °C, including relative permittivity and dielectric loss factor. The temperature effect on AC breakdown properties for MIN-IP and MIX-IP were also researched at 25 °C-75 °C. The result shows that MIX-IP have higher relative permittivity and dielectric loss factor than MIN-IP. The difference on dielectric strength between MIN-IP and MIX-IP is more significant at 45 °C to 65 °C.

1. Introduction

Mixed oil not only has good physicochemical and insulation properties of mineral oil, but also can delay the aging process of cellulose, which is considered to be a potential insulating fluid [1]. Based on preliminary exploration of base oils and mixing ratio, a novel mixed oil (75 vol.% mineral oil + 25 vol.% palm oil) was developed by our team and its main properties basically come up the standards of IEC 60296:2012 [2].

The temperature of oil-immersed transformer is influenced by grid load and ambient temperature, which gives rise to changes in properties of oil-paper insulation system [3]. The dielectric properties of insulating material reflect its performance for storing and consuming electric energy under external electric field [4]. Some dielectric parameters, such as relative permittivity, provide an effective link between the microscopic composition properties of complex system and the macro-system properties, which explain the polarization, relaxation and resonance mechanism of the dielectric microscopic components [5]. Besides, AC breakdown voltages at multiple temperatures of oil-paper insulation system are also important parameters for power transformer. In this work, the dielectric and AC breakdown properties of mineral oil-impregnated paper (MIN-IP) and mixed oil-impregnated paper (MIX-IP) were studied at 25 °C-65 °C. The results can offer the reference for the application of actual transformers using the mineral-palm oil mixture.
2. Experiments

2.1. Samples and Pretreatment

Karamay #25 mineral oil and DL-7 palm oil is the base oil in experiment. The mixed oil is consisted of 75 vol.% mineral oil and 25 vol.% palm oil, and its main parameters is shown in table 1. The insulation paper used in experiment is produced by Yadongya Transformer Company in Chongqing with 0.1 mm thickness.

The mixed oil and mineral oil were dried and degassed for 48 h at 90 ℃/50 Pa to control the oil moisture below 15 ppm. The insulation papers in 4 cm × 4 cm square were dried at 90 ℃ for 24 h. The insulation papers after dry process were respectively impregnated by mineral oil and the mixed oil for 48 hours at 60 ℃/50 pa. The moisture content of MIX-IP and MIN-IP were controlled 0.5%-1%.

Table 1. Basic properties of the mixed oil and mineral oil.

| Property                              | Mixed oil | Mineral oil |
|---------------------------------------|-----------|-------------|
| Kinematic viscosity (40 ℃, mm²/s)     | 6.0       | 9.2         |
| Relative permittivity (90 ℃)          | 2.35      | 2.13        |
| Breakdown voltage (2.5 mm, kV)        | 71        | 70          |
| tan δ (90 ℃)                          | 0.003     | 0.001       |
| Acid value (mg KOH/g)                 | 0.0061    | 0.004       |
| Flash point (90 ℃)                    | 150       | 135         |
| Relative permittivity (90 ℃)          | 2.32      | 2.12        |

2.2. Experiments

Relative permittivity and dielectric loss factor of MIX-IP and MIN-IP were tested by Novocontrol Concept 80 Broadband Dielectric Spectroscopy Equipment at 10⁻¹-10⁷ Hz, and the experimental temperature was controlled from 25 ℃ to 65 ℃ to study the effects on dielectric properties.

The AC breakdown experiment was conducted by IEC 60243. The diameter of the cylinder electrode is 25 mm, while the chamfer of electrode is 3 mm, as shown in Figure 1. Oil container was placed in thermostatic silicone oil to control temperature. The experiment voltage increased at rate of 1 kV/s until breakdown. 12 times breakdown experiments of each type of oil-impregnated paper was tested, and average breakdown voltage was obtained for analysis. The device of AC breakdown test is shown in figure 1.

Figure 1. The device of AC breakdown test.

3. Results and Discussions

3.1. Dielectric Properties for Oil-Impregnated Paper

Figure 2 shows the temperature effect on relative permittivities of MIX-IP and MIN-IP. When the temperature rises, the thermal motion of the particles increases, and the relaxation polarization is
strengthened. So relative permittivities of MIX-IP and MIN-IP has upward trend with temperature increase. As the frequency increases, the change of the electric field direction is much faster than polarization process, which is the reason for inverse correlation between relative permittivity and frequency [6].

Figure 3 gives comparison in relative permittivity between two oil-impregnated papers at 25 °C. Because of the higher relative permittivity of palm oil in mixture, MIX-IP has slightly higher relative permittivity than MIN-IP, especially from 1 Hz to 10³ Hz. This result is mainly caused by the difference on polarity ability between two oil molecules. The main polarization type in palm oil is turning-direction polarization of dipole, while the displacement polarization of electron is dominant for mineral oil molecule. The greater turning-direction polarization leads to the higher relative permittivity of MIX-IP.

![Figure 2](image1.png)

**Figure 2.** The relative permittivities of MIN-IP and MIX-IP.

![Figure 3](image2.png)

**Figure 3.** The comparison in relative permittivities of MIN-IP and MIX-IP at 25 °C.

The dielectric loss factor decreases first and then increases with the increase of frequency, which exists a minimum near 10⁴ Hz, as figure 4 shows. The conductivity loss is main type of dielectric loss in the low-frequency, which show inverse correlation with frequency. When frequency rises high enough, conductivity loss reduces to a small amount, and the polarization loss of dipoles increases with frequency quickly which becomes the main source of dielectric loss [7]. The temperature effect on dielectric loss is affected by frequency, as shown in figure 4. Conductivity loss is the main type of dielectric loss below 10³ Hz, which increases with temperature. When the frequency exceeds 10⁴ Hz, the contribution by polarization loss of dipoles is far greater than conductivity loss, which decline with temperature rise. Because of higher dielectric loss of the mixed oil, MIX-IP has slightly higher dielectric loss factor than mineral one at 10 Hz~10⁴ Hz, as figure 5 shows.
3.2. AC Breakdown Voltages for Oil-Impregnated Paper

The temperature effect on breakdown voltages of MIX-IP and MIN-IP are shown in figure 6. The average breakdown voltage of MIX-IP is 4.18% higher than that of MIN-IP at 25 °C, and this difference rises to 8.91% at 55 °C. The breakdown voltages of MIN-IP and MIX-IP begin to decrease at over 65 °C and 55 °C, respectively. When the experimental temperature increased to 75 °C, the breakdown voltages of MIN-IP and MIX-IP decrease 1.4% and 4.6%, compared with the maximum breakdown voltages. When the temperature continues to rise, the intensification of the molecular thermal vibration will cause the increase of conductance for the oil-paper insulation, which results in the downturn of breakdown voltage with temperature increases.

More uniform electric field distribution between mixed oil and paper is a reason for the advantage on dielectric strength for mixed oil-impregnated paper, which can be obtained by equation (1).

$$\frac{E_{oil}}{E_p} = \frac{\varepsilon_p}{\varepsilon_{oil}}$$

where $\varepsilon_{oil}$ and $\varepsilon_p$, $E_{oil}$ and $E_p$ are the relative permittivities and electric-field intensities of oil and oil-impregnated paper. A electric field simulation was calculated in the three-dimensional model by COMSOL Multiphysics. The maximum electric field is at the contact circumference between the electrode chamfer and the surface of the pressboard. The electric field of MIN-IP is stronger than that of MIX-IP along radial direction, especially at the chamfer of cylinder electrode, as shown in figure 7.
Figure 6. The average breakdown voltages of MIN-IP and MIX-IP.

Figure 7. The electric field distribution of oil-impregnated paper surface and electric-field intensity along radial direction.

Figure 8. The electric field distribution between oil and oil-impregnated paper.

In order to describe the electric field distribution between oil and paper intuitively, the electric-field intensity was obtained along normal direction of oil-impregnated paper surface, while the distance to the axis of the electrode was 10 mm, as shown in figure 8. Take two points (0.03 mm to the oil-paper interface) as an example, the electric-field intensity difference between mixed oil and MIX-IP is defined as $\Delta E_{\text{mix}}$, while the difference between mineral oil and MIN-IP is defined as $\Delta E_{\text{min}}$. While has lower electric-field intensities in oil and its impregnated paper, the mixed oil-paper insulation system also has more uniform electric field distribution between oil-paper ($\Delta E_{\text{mix}} < \Delta E_{\text{min}}$), which induce the advantage on dielectric strength for mixed oil-impregnated paper.
4. Conclusion

Based on a novel mineral-palm oil mixture, the dielectric and AC breakdown properties of the cellulose insulation paper immersed in this mixed oil were studied at multiple temperatures. The conclusions are listed as follows:

(1) The relative permittivity of MIX-IP is slightly higher than that of MIN-IP, increasing as temperature rises. MIX-IP also has slightly higher dielectric loss factor than MIN-IP at 10Hz~10^4Hz. The dielectric loss increases with temperature when the frequency below 10^3 Hz, and shows the opposite trend above 10^3 Hz.

(2) The breakdown voltages of MIX-IP are higher than MIN-IP at 25 °C to 75 °C. When the experimental temperature rises up to 55 °C, the breakdown voltage of MIX-IP begins to decrease with temperature rise.

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Reference

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