A COMPARATIVE STUDY OF MOISTURE AND TEMPERATURE EFFECT ON THE FREQUENCY DIELECTRIC RESPONSE BEHAVIOUR OF PRESSBOARD IMMERSED IN NATURAL ESTER AND MINERAL OIL

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Abstract: It is important to investigate the dielectric behaviour of natural ester-paper insulation as the number of transformer choosing natural ester as its insulation oil is increasing. A comparative study of the influence of moisture and temperature on the frequency dielectric response of pressboard immersed in natural ester and mineral oil was provided. X-Y model simulation was used to indicate the difference between the frequency domain spectroscopy (FDS) characteristics of transformer main insulation system using natural ester-pressboard and mineral oil-pressboard, respectively. Compared to the mineral oil impregnated pressboard with lower moisture content, the natural ester impregnated pressboard with lower moisture content has higher ε_r' and tanδ values in the lower frequency region at various temperatures. While there is no significant difference existing in the ε_r' and tanδ curves of mineral oil impregnated pressboard and natural ester impregnated pressboard with higher moisture content in the lower frequency. X-Y model simulation results show that the dielectric loss difference between natural ester-paper insulation system and mineral oil-paper insulation system with the lower moisture content is more obvious at higher temperature.

1 INTRODUCTION

The main insulation system in a power transformer consists of cellulosic pressboard and insulation oil. It degrades under a combined stress of thermal electrical, mechanical and chemical stresses during routine operations [1-2]. The degradation of transformer insulation is recognized to be one of the major causes of transformer breakdown [3-7]. Thus transformer owners need to assess the status of the main insulation system for safe operation of transformer.

Frequency domain spectroscopy (FDS) is not only a non-destructive dielectric method being widely used to assess the moisture content and ageing condition of oil-paper insulation, but also a diagnosis method which has attracted attention of a large number of scholars and engineers since 1990s. There are many reports about the influence of moisture, ageing and testing temperature on the FDS characteristics of mineral oil-paper insulation [8-12], because the main insulation system of most power transformers is a combination of mineral oil with cellulose materials. However, the performance of mineral oil starts to be limited due to environmental consideration [13-16]. Therefore, nowadays a special focus has been carried out on new alternative insulation liquids for mineral oil [13-16].

Natural esters offer fire safety, environmental and insulation ageing advantages over mineral oil, and are found to be suitable for use in transformer insulation system [13-16]. There are two typical commercial products of natural ester named BIOTEMP made by ABB in 1999 and FR3 developed by Cooper in 2000. These two natural esters have currently been used in small power and distribution transformers. However, there are much limited reports about the frequency dielectric response behaviour of natural ester-paper insulation though the number of transformer choosing natural ester as its insulation oil is increasing. Gracakowski [17] analyzed the frequency dielectric response characteristics of pressboard immersed in synthenic ester MIDEL 7131 and mineral oil. It was observed that type of impregnating liquid has significant influence on dielectric response of pressboard. Thus, it is required to investigate the FDS characteristics of the natural ester-paper insulation.

Knowing the FDS characteristics of natural ester-paper insulation with different moisture contents at different temperature is helpful to make an accuracy assessment of the moisture content in transformer using natural ester. In this paper, a comparative result of the influence of moisture and temperature on the frequency dielectric response of pressboard immersed in natural ester (PINE) and pressboard immersed in mineral oil (PIMO) was provided. The X-Y model simulation was used to indicate the FDS characteristic difference between the transformer main insulation system using natural ester-pressboard and mineral oil-pressboard, respectively.

2 THEORY

2.1 Frequency domain spectroscopy

When an AC sinusoidal voltage source $u(t)=U^*\sin(\omega t)$ is applied across a parallel plate capacitor incorporating a dielectric material, the material polarize at different frequencies to a varying extend. The resulting current is made up of two components: the charging current (I_{charge}) and the loss current (I_{loss}), both being related to the complex permittivity. The total current flowing through the insulator is given by [18, 19]:

$$I=I_{charge}+I_{loss}=U^*(j\omega C+G) \qquad (1)$$

Let $C=\varepsilon_r' C_0$ and $G=\omega C_0\varepsilon_r''$, then,

$$\begin{aligned} I &= U(j\omega\varepsilon_r' C_0+\omega C_0\varepsilon_r'') \\ &= j\omega C_0 U(\varepsilon_r'-j\varepsilon_r'') \\ &= j\omega C_0 U\varepsilon_r^* \end{aligned} \qquad (2)$$

where C is the capacitance of the material under test between the electrodes, C_0 is the vacuum capacitance. The $\varepsilon_r^*=\varepsilon_r'-j\varepsilon_r''$, and the $\tan\delta=I_{loss}/I_{charge}=\varepsilon_r''/\varepsilon_r'$

2.2 X-Y model of transformer main insulation system

The main insulation system of transformer consists of cylindrical pressboard barriers in series with oil ducts and spacers, as shown in Figure 1 [20]. By combining all oil ducts, barriers and spacers, the main insulation system can be simplified as X-Y model, as presented in Figure 2 [21]. The parameters X and Y in the model can be represented by equation (3):

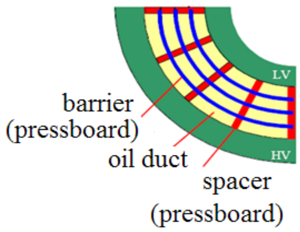


Figure 1. Section of main insulation in a core-type transformer

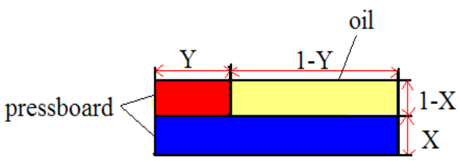


Figure 2. X–Y representation of transformer main insulation

$$X=\frac{thickness..of..total..barriers}{width..of..the..duct}$$

$$Y=\frac{total..width..of..the..spacer}{width..of..the..duct} \qquad (3)$$

The X-Y model is widely used for the diagnostics of transformer insulation [22]. The dielectric response across the X-Y system can be calculated when the individual dielectric response of oil and spacers (barriers) are known. In real power transformers, X and Y vary often between 0.2-0.5 and 0.15-0.25, respectively [21]. The total relative complex permittivity of the X-Y model shown in Figure 2 at testing temperature T can be described as [21]:

$$\varepsilon_r^*(\omega,T)=\frac{Y}{\dfrac{1-X}{\varepsilon^*_{r-spacer}(\omega,T)}+\dfrac{X}{\varepsilon^*_{r-barrier}(\omega,T)}}+\frac{1-Y}{\dfrac{1-X}{\varepsilon^*_{r-oil}(\omega,T)}+\dfrac{X}{\varepsilon^*_{r-barrier}(\omega,T)}} \qquad (4)$$

where,

$$\varepsilon^*_{r-spacer}(\omega,T)=\varepsilon^*_{r-barrier}(\omega,T)=\varepsilon^*_{r-pressboard}(\omega,T)$$

$$\varepsilon^*_{r-oil}(\omega,T)=\varepsilon_{r-oil}-j\frac{\sigma(T)}{\varepsilon_0\omega} \qquad (5)$$

In this paper, the X-Y model equations were used to simulate the FDS characteristics of transformer using natural ester-pressboard or mineral oil-pressboard as main insulation system.

3 EXPERIMENTAL

3.1 Experiment materials and equipment

The insulation pressboard used in the experiment was provided by Hunan No.1 Insulation Pressboard Co. Ltd, China. The technical performances of the pressboard satisfy the international standard IEC 641-3-1. The pressboard has a thickness of 0.3mm for a single layer. The pressboard was cut into circle samples with diameter of 42 mm. The mineral oil used in this experiment was Karamay 25# naphthenic mineral oil provided by Chuanrun Lubricant Co. Ltd, China. The natural ester used in this research was BIOTEMP natural ester provided by ABB Chongqing Transformer Co. Ltd.

The FDS measurements were carried out using Novocontrol Concept 80 Broadband Dielectric Spectroscopy equipment. The test electrode diameter for pressboard sample was 40mm. The principle of FDS is shown in Figure 3. The electrode was put into a sealed vessel enclosed in the equipment when the FDS measurement was performed. In this way, the constant moisture equilibrium and temperature can be maintained during the measurement period.

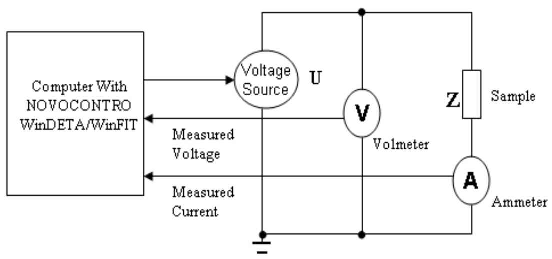


Figure 3. FDS measurement circuit

3.2 FDS of oil impregnated pressboard with lower and higher moisture content

In order to achieve different moisture contents in the pressboard, firstly, all pressboard samples were put into a vacuum box and were dried at 90°C for 48 hours. Secondly, the pressboard samples were taken out the vacuum for moisture absorption in the air. And then the pressboard samples with different moisture absorption times were immersed in the new mineral oil and new natural ester contained in bottles, respectively. Thirdly, the bottles containing oil/pressboard samples were put into the vacuum box for impregnation at 40°C for 48 hours. And then the vacuum box was cooled down to room temperature naturally. Finally, the pressboards immersed in mineral oil or natural ester were taken out for moisture content test by Karl Fischer titration unit (METTLER TOLEDO DL32), and for FDS test at different temperatures. The variation of the testing temperature was 10°C, 30°C, 50°C, 70°C and 90°C. The frequency range is form 10^{-2} to 10^{6}Hz.

4 RESULTS AND DISCUSSIONS

4.1 FDS of oil impregnated pressboard with lower moisture content

Figure 4 and Figure 5 show the behaviours of the ε_r' and tanδ for the natural ester impregnated pressboard and mineral oil impregnated pressboard with nearly same lower moisture content at varied temperatures. The changing behaviour of ε_r' and tanδ of natural ester impregnated pressboard is similar to mineral oil impregnated pressboard. However, the natural ester impregnated pressboard with lower moisture content has higher ε_r' and tanδ values in the lower frequency region at various temperatures.

With the increasing of temperature, the values of ε_r' and tanδ increase at lower frequencies. This is because with the temperature increased, the ions mobility in oil could be enhanced. The dipole-dipole interactions due to the increased mobility of flexible portions in the cellulose chains decrease with the increase of testing temperature, which enhances the ease of rotation and polarizability of the side groups and of other flexible portions of cellulose [23]. All the ε_r' or tanδ values decrease with the increasing frequency at each testing temperature. This is because more polarization processes can be completed under lower frequency. With the increasing of electric field frequency, the dipoles cannot follow the faster changing electrical field instantaneously or not at all, so the ε_r' decreases with the increasing frequency until reaching a relative stable value.

The values of tanδ decreases with the increasing frequency first, and then increase again with the frequency increased at each testing temperature.

The tanδ can be calculated as follows [24]:

$$\tan\delta = \left[\frac{r}{\omega\varepsilon_0} + (\varepsilon_s - \varepsilon_\infty)\frac{\omega\tau}{1+\omega^2\tau^2}\right] \Big/ \left[\varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\omega^2\tau^2}\right]$$

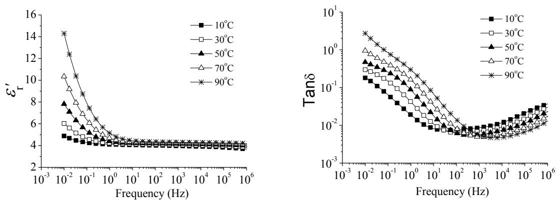
Where, γ is the conductivity, τ: is the time constant of relaxation polarization, ε_s is static dielectric constant, $\varepsilon_\infty$is optical dielectric constant, ω is the angular frequency.

When $\omega\tau$ <<1,

$$\varepsilon = \varepsilon_\infty + [(\varepsilon_s - \varepsilon_\infty)/(1+\omega^2\tau^2)]$$

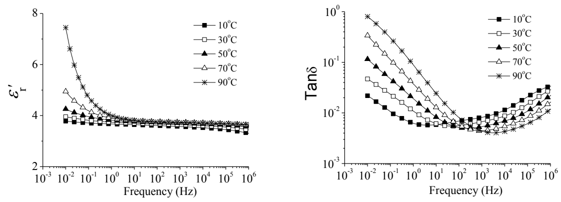
$$\tan\delta = r/\omega\varepsilon_0\varepsilon_s$$

Therefore, the value of tanδ decreases with the frequency in a reciprocal way. As the increase of test frequency continuing, $\omega\tau \to 1$, the variation period of the electric field becomes close to the relaxation time, the relaxation polarization is then very sensitive to the variation of the electric field, the increase in the polarization loss makes the increment rate of the active current exceed that of the reactive current. Consequently the tanδ increases with the increase of frequency.



(a) ε_r' (b) tanδ

Figure 4. FDS of natural ester impregnated pressboard with 1.24% moisture content



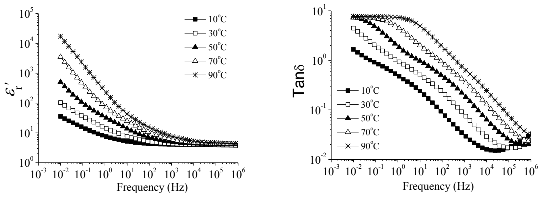
(a) ε_r' (b) tanδ

Figure 5. FDS of mineral oil impregnated pressboard with 1.27% moisture content

4.2 FDS of oil impregnated pressboard with higher moisture content

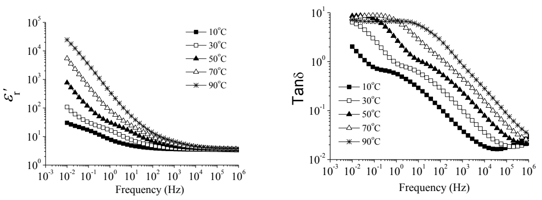
Figure 6 and Figure 7 show the behaviours of the ε_r' and tanδ for the natural ester impregnated pressboard and mineral oil impregnated pressboard with nearly same higher moisture content at varied temperatures. The results also clearly show that the changing behaviour of ε_r' and tanδ of natural ester impregnated pressboard is similar to mineral oil impregnated pressboard. There is no significant difference in the ε_r' and tanδ curves in the lower frequency region at various temperatures. However, ε_r' and tanδ value of natural ester impregnated pressboard and mineral oil impregnated pressboard with the same higher moisture content are very different from the results presented in Figure 4 and Figure 5.

Compared with ε_r' and tanδ behaviours of oil impregnated pressboard with lower moisture content, at the same testing temperature, it is noteworthy that for the oil impregnated pressboard with higher moisture content ε_r' and tanδ values are all higher, and the frequency is higher when the ε_r' reaching a relative stable value. In addition, an obvious local peak in the loss factor curve arises when the moisture content is higher, and shifts towards higher frequencies with increasing temperature. The frequency where the tanδ is minimal also shifts to higher frequency with the temperature increasing. However, the frequency at which the tanδ is minimal higher than 10^6 Hz when the temperature is higher than 30°C, which can't be seen in the testing frequency range.



(a) ε_r' (b) tanδ

Figure 6. FDS of natural ester impregnated pressboard with 3.92% moisture content



(a) ε_r' (b) tanδ

Figure 7. FDS of mineral oil impregnated pressboard with 3.96% moisture content

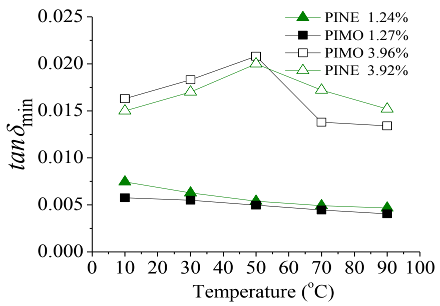


Figure 8. The minimal tanδ for oil impregnated pressboard with lower and higher moisture content

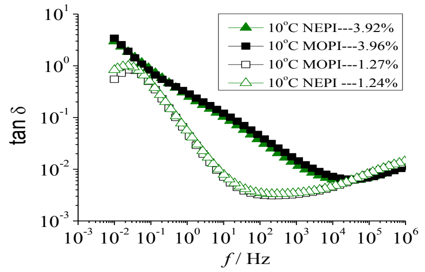
The minimal tanδ for oil impregnated pressboard with lower and higher moisture content in the frequency range of 10^{-2}Hz~10^6Hz is summarized in Figure 8. The minimal tanδ of mineral oil impregnated pressboard with lower moisture content is lower than that of natural ester impregnated pressboard with lower moisture content. While the minimal tanδ of mineral oil impregnated pressboard with higher moisture content is larger than that of natural ester impregnated pressboard at 10°C, 30°C, 50°C, and it is contrary at 70°C and 90°C.

4.3 X-Y model simulation of oil-pressboard insulation system with lower and higher moisture content

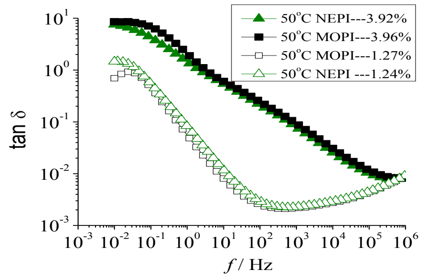
As we all know tanδ=$\varepsilon_r''/\varepsilon_r'$, we can obtain the ε_r' values of oil impregnated pressboard with lower and higher moisture content at different temperature from the ε_r' and tanδ results above. And we can also get the ε_r'' values of the sample simultaneously when the FDS test was conducted using Novocontrol Concept 80 Broadband Dielectric Spectroscopy equipment. Then the FDS characteristics of transformer with different conditions can be simulated by the X-Y model, as presented in section 2.1.

In this paper, we simulated the FDS characteristics of the transformer main insulation system having same geometry construction and moisture content, just using natural-ester pressboard and mineral oil-pressboard as main insulation system, respectively. Taking into account that the oil conductivity has influence on the FDS behaviour of transformer insulation, the higher the oil conductivity, the larger magnitude of the dielectric loss curve shifted to the higher frequency [21]. In the simulation section, the permittivity of mineral oil was set as 2.3, and natural ester 3.2. Firstly, the oil conductivity of mineral oil and natural ester was set as 1×10^{-11} s/m, and the X=0.2, Y=0.25. Secondly, the mineral oil conductivity and natural ester oil conductivity was set as 1×10^{-10} s/m, and the X=0.2, Y=0.25.

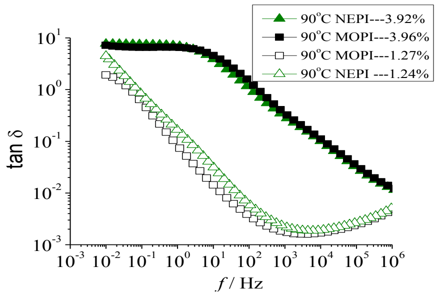
For oil conductivity of mineral oil and natural ester is equal to 1×10^{-11} s/m, the dielectric loss behaviours simulated are shown in Figure 9. It can be seen that when the moisture content of the main insulation system is lower, and under lower testing temperature, the dielectric loss differences of the transformer using natural ester-pressboard insulation (NEPI) and mineral oil-pressboard insulation (MOPI) as the main insulation system respectively are not notable. However, with the testing temperature increased, the dielectric loss difference become much notable below 10^3Hz at 90°C. When the moisture content of the main insulation system is higher, the dielectric loss differences of the transformer using natural ester-pressboard and mineral oil-pressboard as the main insulation system respectively are not obvious, as shown in Figure 9. For the oil conductivity of mineral oil and natural ester is equal to 1×10^{-10} s/m, the dielectric loss behaviours simulated are shown in Figure 10. It can be seen that when the moisture content of the main insulation system is lower, the dielectric loss differences of the transformer using natural ester-pressboard and mineral oil-pressboard as the main insulation system respectively are much obvious in the lower frequencies. When the moisture content of the main insulation system is higher, there is no big difference in the dielectric loss of the transformer using natural ester-pressboard and mineral oil-pressboard as the main insulation system respectively. Therefore, when one using FDS equipment to assess the moisture content of a transformer using natural ester, the kind of insulation liquid must be considered at higher testing temperature when the moisture content is lower.



(a) 10°C

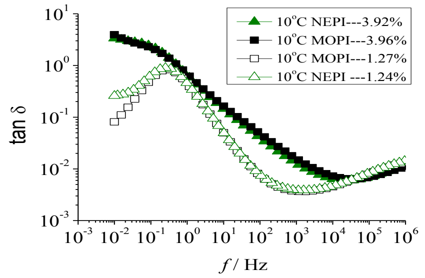


(b) 50°C

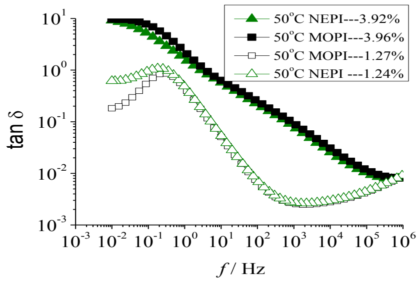


(c) 10°C

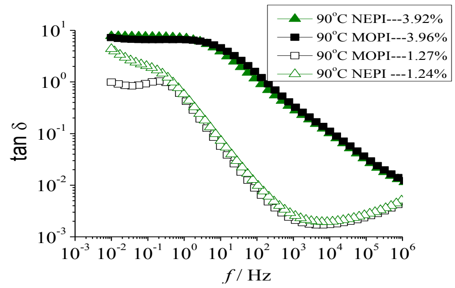
Figure 9. Dielectric loss of main insulation system with oil conductivity 1×10^{-11} s/m



(a) 10°C



(b) 50°C



(c) 90°C

Figure 10. Dielectric loss of main insulation system with oil conductivity 1×10^{-10} s/m

5 CONCLUSIONS

The moisture and temperature have great effect both on the natural ester impregnated pressboard and mineral oil impregnated pressboard. The natural ester impregnated pressboard with lower moisture content has higher ε_r' and tanδ values in the lower frequency region at various temperatures compared with the mineral oil impregnated pressboard with lower moisture content. While there is no big difference exiting in the ε_r' and tanδ values of mineral oil impregnated pressboard and natural ester impregnated pressboard with higher moisture content in the lower frequency region at various temperatures.

X-Y model simulation results show that when the moisture content of the main insulation system is lower, the dielectric loss difference of the transformer using natural ester-pressboard and mineral oil-pressboard as the main insulation system respectively are more notable at higher temperature, but there is no big difference when the moisture content of the main insulation system is higher.

6 ACKNOWLEDGMENTS

All the authors thank Chinese National Basic Research 973 Program of China (2009CB724505-1) and the Scientific Research Foundation of SKL of Power Transmission and System Security (2007DA10512708103) for the financial support provided.

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