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Influence of temperature on Cole-Cole dielectric model of oil-immersed bushing

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Abstract. In this paper, 72.5 kV oil-immersed bushing was produced in laboratory. The frequency-domain dielectric response tests of oil-immersed bushings were carried out at different test temperatures. The experimental data were fitted by using the modified double relaxation Cole-Cole dielectric model. The influence of temperature variation on the dielectric response test of the oil-immersed bushing and the Cole-Cole dielectric model parameters were analysed. The results showed that with the increase of the test temperature, the spectrum of the real and imaginary of the complex permittivity are shifted to the high frequency direction; the parameters of the dielectric model are significantly affected by temperature.

1. Introduction
Insulation performance of oil-immersed bushing will directly affect the safety and stability of the transformer operation. The frequency domain dielectric response method is one of the methods used for lossless insulation diagnosis [1-2]. The modified Cole-Cole model [3-4] can better explain the dielectric properties of the dielectric in the frequency domain, and more suitable for field applications.

In this paper, 72.5 kV oil-immersed bushing was produced in laboratory. The frequency-domain dielectric response tests of oil-immersed bushings were carried out at different test temperatures. The experimental data were fitted by using the modified double relaxation Cole-Cole dielectric model. The influence of temperature variation on the dielectric response test of the oil-immersed bushing and the Cole-Cole dielectric model parameters were studied.

2. Experiment

2.1. Pretreatment of experimental materials
The internal insulation materials of the oil-immersed bushing model are the paper (thickness is about 0.1 mm) and the 45#oil. The electrode screen is 0.03 mm aluminum foil. The center duct is a hollow aluminum tube. In order to reduce the influence of the moisture content, the following pretreatment of paper and oil was carried out: The paper was cut according to the pre-calculated size; the cut paper was dried at 110 °C/50 Pa for 72 h; so that the water content was less than 0.5%. The oil was degassed and dried at 80 °C until the moisture content was about 11 ppm.

2.2. Preparation of bushing model

According to insulation structure and design specifications of 72.5 kV high voltage bushing, the bushing model was prepared. The structure of capacitance core is shown in Figure 1. In order to eliminate the influence of moisture in the air during the winding process, the capacitor core was dried in a drying oven at 110 °C for 24 h after the bushing was completed. The dried oil-immersed bushing capacitor core was sealed in an epoxy tube and immersed in insulating oil for 48 h under 40 °C.

Figure 1. Structure of capacitance core.

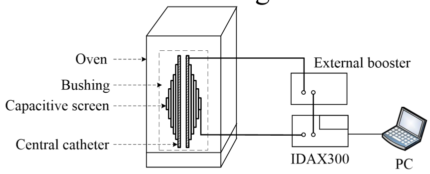


Figure 2. Experiment wiring diagram.

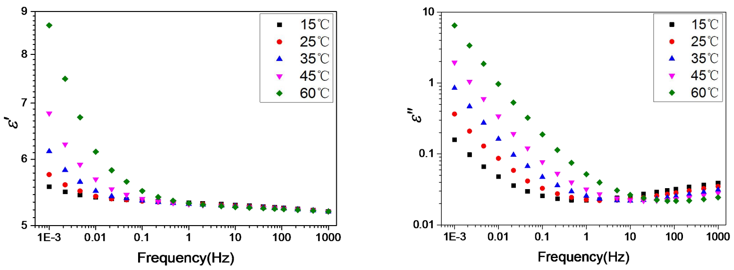
2.3. Experiment process

The dielectric response test was carried out at 15 °C, 25 °C, 35 °C, 45 °C, and 60 °C, respectively. The bushing model was placed in the oven and allowed to stand at a preset temperature for 24 h. IDAX300 is used to test the frequency domain dielectric response of the oil-immersed bushing model. The test frequency ranges 0.001 Hz~1000 Hz. The moisture content of the bushing model is 0.53%. Figure2 shows the experimental wiring diagram of this experiment.

3. Analysis of experimental results based on the double relaxation Cole-Cole model

3.1. Experimental results

Figure3 is the spectrum diagram of the real part and the imaginary part of the complex permittivity of the oil-immersed bushing model. The results show that with the increase of the test temperature, the spectrum of the real and imaginary of the complex permittivity are shifted to the high frequency direction.



(a) ε' **(b)** ε''

Figure 3. Complex permittivity.

3.2. Establishment of double relaxation Cole-Cole model

It can be seen from Figure3 that the spectrum of the imaginary part of the complex permittivity has a transition in the vicinity of 10 Hz, which indicates that the frequency-domain dielectric response characteristics in the test band are at least include two relaxation process. Therefore, in this paper, the dielectric properties of oil-immersed bushing in the frequency domain were fitted by α relaxation process and β relaxation process. The equation (1) is the modified double-relaxation Cole-Cole model equation for oil-immersed bushing.

$$\varepsilon(\omega)=\varepsilon_{\infty}+\frac{\sigma_{dc}}{j\varepsilon_0\omega}+\frac{\Delta\varepsilon_1}{1+(j\omega\tau_1)^{\alpha_1}}+\frac{\Delta\varepsilon_2}{1+(j\omega\tau_2)^{\alpha_2}} \quad (1)$$

Where: ε_∞ is the high frequency dielectric constant; $\Delta\varepsilon_1$, $\Delta\varepsilon_2$ are the relaxation strength of α relaxation process and β relaxation process respectively; α_1, α_2 are the distribution parameters of α relaxation process and β relaxation process; τ_1, τ_2 are the relaxation time of α relaxation process and β relaxation process; σ_{dc} is the direct current conductivity of oil-immersed bushing, $pS\cdot m^{-1}$.

The formula (1) is divided into real and imaginary parts, then the real and imaginary parts of the complex permittivity of the oil-immersed bushing can be expressed as the following formulas:

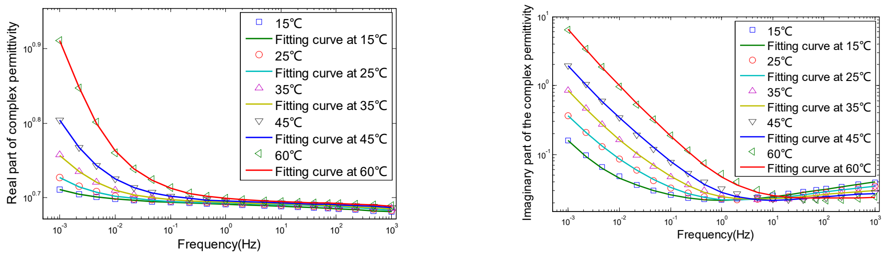
$$\varepsilon' = \varepsilon_\infty + \mathrm{Re}[\frac{\Delta\varepsilon_1}{1+(j\omega\tau_1)^{\alpha_1}} + \frac{\Delta\varepsilon_2}{1+(j\omega\tau_2)^{\alpha_2}}] \tag{2}$$

$$\varepsilon'' = \frac{\sigma_{dc}}{\varepsilon_0\omega} - \mathrm{Im}[\frac{\Delta\varepsilon_1}{1+(j\omega\tau_1)^{\alpha_1}} + \frac{\Delta\varepsilon_2}{1+(j\omega\tau_2)^{\alpha_2}}] \tag{3}$$

Where: ε_∞, $\Delta\varepsilon_1$, $\Delta\varepsilon_2$, α_1, α_2, τ_1, τ_2, σ_{dc} are unknown parameters, and the least squares method can be used to fit results of the experiment so that the unknown parameters can be obtained.

3.3. Analysis of results based on double relaxation Cole-Cole model

The fitting curve of the real and imaginary parts of the complex permittivity of the bushing model are shown in Figure 4. At the same time, the unknown parameters in equation(2) and equation(3) are obtained by fitting and are shown in Table 1.



(a) ε' **(b)** ε''

Figure 4. Complex permittivity curve.

Table 1. Parameters of Cole-Cole model of oil-immersed bushing at different temperatures

Parameters	15 ºC	25 ºC	35 ºC	45 ºC	60 ºC
σ_{dc}/(S/m)	6.70E-09	1.64E-08	4.05E-08	9.42E-08	3.24E-07
$\Delta\varepsilon_1$	0.180 497	0.282 454	0.503 608	1.005 245	2.342 287
τ_1/s	39 343.57	7 856.422	488.568 2	756.377 1	447.442 6
α_1	0.476 818	0.561 242	0.577 932	0.607 662	0.668 282
$\Delta\varepsilon_2$	0.497 421	0.745 339	0.464 511	0.290 165	0.396 576
τ_2/s	4.90E-09	3.59E-09	3.43E-09	3.27E-09	1.70E-09
α_2	0.223 823	0.251 027	0.254 668	0.268 09	0.308 281
ε_∞	3.339 657	3.007 481	3.174 107	2.871 314	2.884 781

4. Discussion

4.1. Influence of temperature on DC conductivity

The fitting relation curve shown in Figure5 and the fitting relation shown in equation (4). It can be seen from Figure5 and equation (4) that the oil-immersed bushing increases exponentially with the increase of the temperature *T*, which meets the study that the DC conductivity and temperature *T* satisfy the Arrhenius equation.

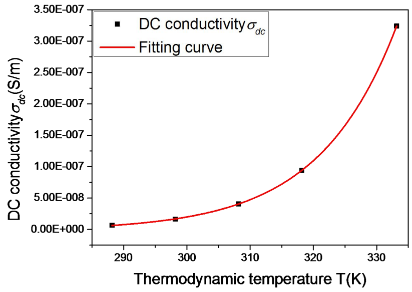
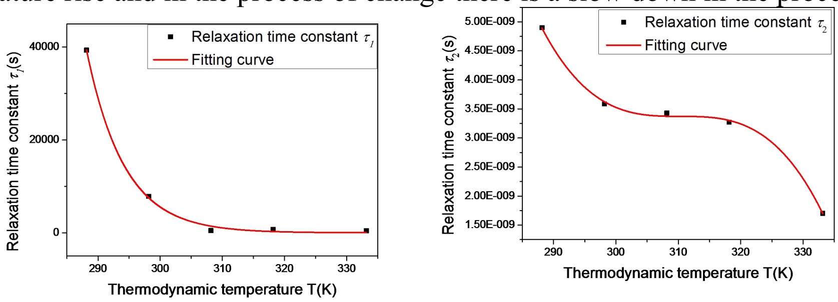


Figure 5. The fitting curves of DC conductivity and temperature.

$$\sigma_{dc} = 48658.56 \exp(-\frac{1.1833 \times 10^{-19}}{1.38 \times 10^{-23} T}) \tag{4}$$

4.2. *Influence of temperature on relaxation time constant*

The fitting curve of the relaxation time and the temperature T is shown in Figure6.The fitting relation shown in equation (5) is obtained by fitting the relationship between the relaxation time and the thermodynamic temperature in Table 1. From Figure 6, it can be seen that the relaxation time τ_1 decreases exponentially with the increase of the test temperature and the relaxation time τ_2 decreased with the temperature rise and in the process of change there is a slow down in the process of declining.



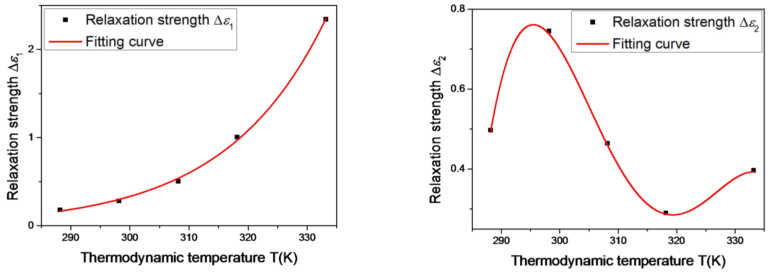
(**a**)Relaxation time τ_1 (**b**) Relaxation time τ_2

Figure 6. The fitting curve of relaxation time and temperature.

$$\begin{aligned} \tau_1 &= 1.8452 \times 10^{25} \exp(-0.16518T) \\ \tau_2 &= 4.173 \times 10^{-6} - 4.032 \times 10^{-8} T + 1.299 \times 10^{-10} T^2 - 1.396 \times 10^{-13} T^3 \end{aligned} \tag{5}$$

4.3. *Influence of temperature on relaxation strength*

The relaxation strength and temperature in Table 1 are fitted to obtain the fitting curve of the relaxation strength and temperature T shown in Figure 7, and the fitting relation is obtained as shown in equation (6). Figure 7 shows that the dielectric relaxation strength $\Delta\varepsilon_1$ of the Cole-Cole model increases exponentially with the increase of temperature and $\Delta\varepsilon_2$ showed a tendency to increase first, then decrease and then increase with the increase of test temperature.



(**a**)Relaxation strength $\Delta\varepsilon_1$ (**b**) Relaxation strength $\Delta\varepsilon_2$

Figure 7. The fitting curves of relaxation strength and temperature.

$$\begin{aligned} \Delta\varepsilon_1 &= 6.94813\times 10^{-9}\exp(0.05895T) \\ \Delta\varepsilon_2 &= -20248.256 + 257.315T - 1.225T^2 + 0.00259T^3 - 2.047\times 10^{-6}T^4 \end{aligned} \quad (6)$$

5. Conclusion

1) With the increase of the test temperature, the spectrum of the real and imaginary of the complex permittivity are shifted to the high frequency direction.

2) the DC conductivity and thermodynamic temperature satisfy Arrhenius relation; the relaxation time τ_1 decreased exponentially with the increase of test temperature; τ_2 decreased with the temperature rise and in the process of change there is a slowdown; the relaxation strength $\Delta\varepsilon_1$ exponentially increased with the increase of test temperature; $\Delta\varepsilon_2$ showed a tendency to increase first, then decrease and then increase with the increase of test temperature.

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