Study on Temperature Characteristics of Frequency -domain Dielectric Spectrum of Capacitive Oil-paper Insulation Bushing Based on Extended Debye Model

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Abstract. In order to study the influence of temperature on the frequency domain spectroscopy (FDS) of the oil-paper insulation system, the 72.5kV bushing test model was fabricated according to the actual size, and the FDS of the bushing was tested at different temperatures. According to the test curves of the dielectric constant at different temperatures, the influence of temperature on FDS is analysed, and then the extended Debye equivalent circuit model is used to fit the FDS test curves at different temperatures. The characteristic parameters that could be used to characterize the temperature characteristics are extracted, and the relationship between the characteristic parameters and the temperature is established. The results show that dielectric constant tend to move in the high frequency with the increase of temperature. The parameters of the equivalent circuit model are sensitive to the temperature, the insulation resistance R_g and the maximum time constant branch parameter R_1 show the exponential function with the temperature, the minimum time constant branch parameter R_3 and the temperature show a power function relationship, so the variation of characteristic parameters can be applied to evaluate the influence of temperature on the FDS of the oil-paper insulation bushing.

1. Introduction

Capacitive oil-paper insulation bushing as the insulation and mechanical support equipment of the transformer. its insulation performance directly affects the reliability of the transformer operation [1-2]. The dielectric response based on the frequency-domain dielectric spectroscopy (FDS) used to assess and diagnose the transformer insulation state has been extensively studied [3]. The method of constructing function model to extract the characteristic parameters can be used to quantify the influence of temperature on FDS measurement results [4]. The resistance and capacitance parameters of the branch circuit of the extended Debye model can explain the loss characteristics of oil-paper [5-6].

Based on the extended Debye model, the influence of temperature on FDS of the bushing is studied in this paper. First, 72.5kV bushing test model was fabricated according to the actual size. The dielectric spectra of the bushing in different frequency were measured. And then use the extended Debye equivalent circuit model to fit the FDS test curve at different temperatures, then the relationship between the characteristic parameters and the temperature is extracted and established.

2. Experiment

2.1. Preparation of sample

The sample studied in this paper is based on a laboratory-made 72.5 kV bushing model which the thickness of the cable paper used to produce the capacitor core is 0.1 mm and the thickness of the aluminum foil plate is 0.03 mm, and degassed 45 # transformer oil. Insulated paper was placed in 101-1A electric blast drying oven under the environment of 110 ℃/50pa for 72h. The moisture content of the paper was reduced to below 0.5% through using the METTLER TOLEDO C20 Karl Fischer water titrator to titrate. Degassed 45 # transformer oil was placed in a vacuum drying oven under the environment of 80 ℃/50p for 48h, water titrator titrated the oil until the moisture content down to 10ppm or less.

The insulation layer of inner insulation core is set 17 layers, the capacitance core outside diameter is 30.4mm, aluminum foil and cable paper are cut according to the calculated size of the capacitor core, hollow aluminum tube is set as the center, the cable paper is tightly wrapped around the aluminum tube, as a certain thickness is wounded and then add a layer of aluminum foil as a capacitive screen. The wounded capacitor core model is shown in Figure 1.

2.2. Test plan

Before the test, the bushing was placed in the oven under the environment of 40 ℃/ 50pa for 48h to keep the insulating paper fully immersed in oil. Then adjust the temperature of the oven to test the FDS curve at different temperatures. The selected test temperature was 15 ℃, 25 ℃, 35 ℃, 45 ℃, 60 ℃. IDAX-300 as the test tool of FDS curve, the selected frequency range is 1mHz-1kHz. The moisture content of the oil-immersed bushing model is 0.53%. FDS test wiring is shown in Figure 2.
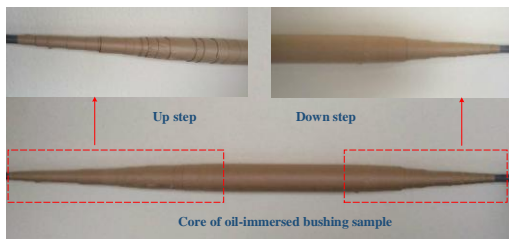
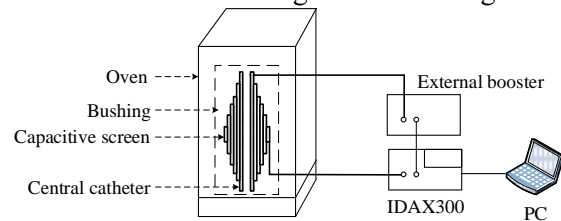

Figure 1. 72.5kV capacitor core model.

Figure 2. FDS test wiring diagram.

3. Result analysis

Figure 3 shows the 0.53% water content of oil -paper insulation of the bushing at different temperatures, the measurement results of the complex permittivity of the real part ε' and the imaginary part ε'' change with the change of frequency.

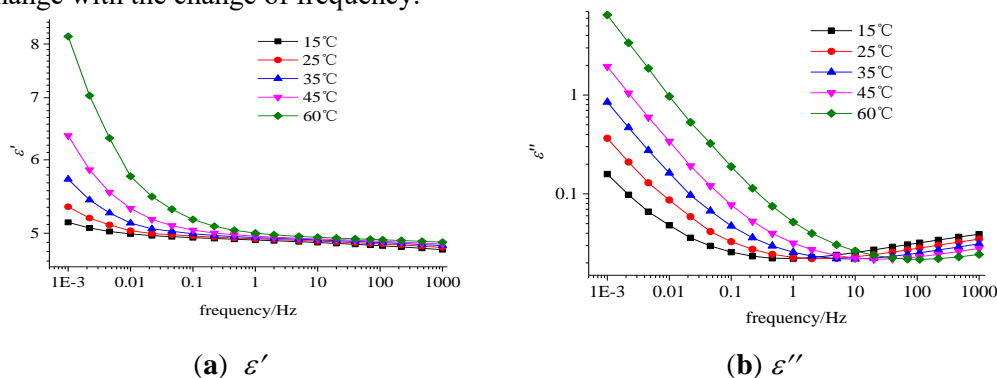(**a**) ε' (**b**) ε''

Figure 3. the dielectric constant at different temperatures.

It can be seen from Figure 3 that the influence of temperature on the FDS test curve, in the range of 0.001-1000Hz, ε' increases with the increase of temperature when the frequency is less than 1Hz，and ε' does not change with the increase of temperature when the frequency is more than 1Hz. ε'' increases in the range of 0.001 to 10 Hz with the increase of temperature and decreases in the range of

10-1000 Hz with the increase of temperature. instantaneous polarization plays a leading role in the high frequency band results that ε' basically does not change with the change of temperature when the frequency is more than 1Hz. The main reason why ε'' changes is that when the temperature rises, the thermal motion of the conductive particles increases and the conductance loss becomes larger. The conductivity loss decreases with the increase of temperature, while the relaxation time constant associated with polarization decreases with the increase of temperature, the higher the temperature is, the shorter the settling time will be, and ε'' tends to shift to the right. In the high frequency band, ε'' appears to decrease with the increase of temperature.

4. Extended Debye equivalent circuit model of oil - paper insulation bushing

4.1. Extraction of the characteristic parameters

The main insulation system of bushing consists of multiple layers of insulating paper, the oil gap between paper and paper, aluminum foil that can make voltage and electric field uniform. oil-paper insulation system can be simplified to the extended Debye equivalent circuit model shown in Figure 4, where R_g represents the insulation resistance of the oil-paper insulation system, C_g is the geometric capacitance, and the R_i-C_i branch circuit represents the lossy relaxation polarization at different relaxation time [7].
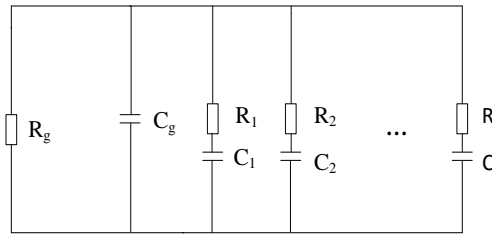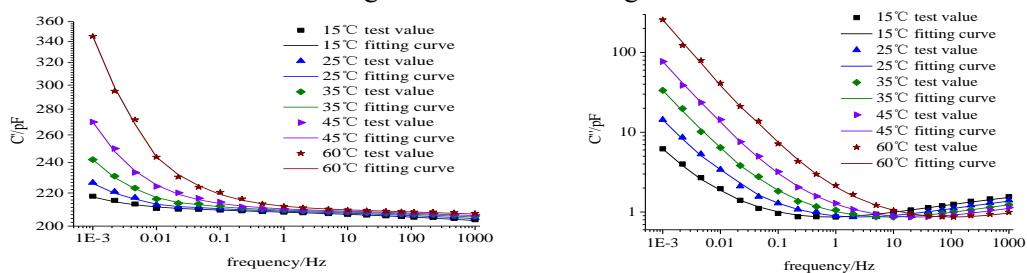

Figure 4. Debye equivalent circuit model of oil-paper insulation.

It is known that the Debye equivalent circuit model can be used to calculate the complex capacitance expression of the dielectric properties of oil-paper insulation of the bushing. Real part, imaginary part of complex capacitance can be expressed as:

$$C'(\omega) = \mathrm{Re}\{\frac{1}{j\omega Z}\} = C_g + \sum_{i=1}^{n}\frac{C_i}{1+(\omega R_i C_i)^2} \tag{1}$$

$$C''(\omega) = -\mathrm{Im}\{\frac{1}{j\omega Z}\} = \frac{1}{\omega R_g} + \sum_{i=1}^{n}\frac{\omega R_i C_i^2}{1+(\omega R_i C_i)^2} \tag{2}$$

It can be seen from Figure 4 that each branch circuit has the same characteristics of the parameters, in order to simplify the model, we take the above expression n = 3. According to the frequency domain dielectric curve of 0.53% water content of complex capacitance of bushing in different temperature conditions, least squares method is used to fit complex capacitor expression (1) , expression (2) and the frequency domain dielectric curve of complex capacitance. The obtained characteristic parameter values are shown in Table 1. The fitting curve is shown in Figure 5.

(a) C′   **(b)** C″

Figure 5. FDS test values and fitting curves of bushing at different temperature.

Table 1. Fitting parameter values of Debye equivalent circuit model at different temperatures

Temperature/℃	C_g/pF	R_g/GW	C_1/pF	R_1/GW	C_2/pF	R_2/GW	C_3/pF	R_3/GW
15	203.845	26.449	8.055	7.079	2.871	0.142	3.397	0.00068
25	205.039	11.479	6.613	3.989	2.427	0.292	3.2	0.00098
35	206.414	5.069	31.922	2.611	17.142	0.666	3.353	0.00364
45	207.62	2.207	57.488	1.656	15.299	0.511	4.457	0.01557
60	208.951	0.661	122.795	0.781	36.165	0.303	10	0.04245

Figure 5 shows that the frequency domain dielectric curve of complex capacitance and Debye dielectric response models have very good goodness of fit, It can be seen from Table 1, R_i, C_i each has a corresponding characteristic of the change with the increase of temperature, Where the insulation resistance R_g and the maximum and minimum time constant branch resistance R_i (i =1,3) are more sensitive to temperature, which is more obvious and regular with the change of temperature, so the relationship between these three parameters and temperature is selected as a research object.
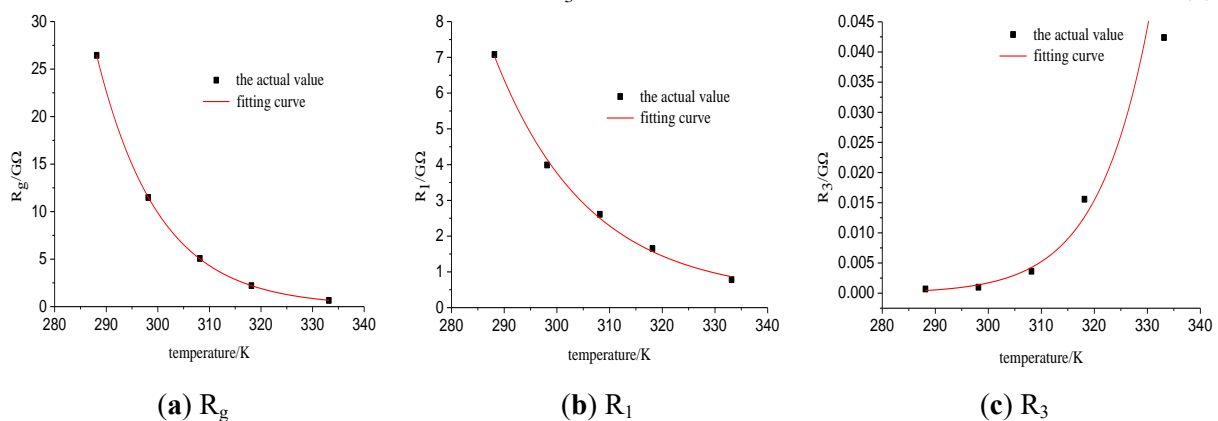
4.2. Influence of temperature on characteristic parameters
Figure 5 shows the relationship between selected characteristic parameters and temperature. It can be seen from Figure 6 that the selected characteristic parameters and temperature separately show a quantitative relationship, the parameters and the corresponding test temperature are fitted separately, then the fitting formula shown in equation (3), equation (4) and equation (5) can be obtained.

$$R_g = A_0\, e^{(-T/B_0)} + C_0 \tag{3}$$

$$R_1 = A_1\, e^{(-T/B_1)} + C_1 \tag{4}$$

$$R_3 = a \times T^b \tag{5}$$

(a) R_g **(b)** R_1 **(c)** R_3

Figure 6. The relationship between the characteristic parameters and temperature.

The equation parameters obtained in this study are: A_0=7.3×1011, B_0=11.98, C_0=0.5542, A_1=7.89×107, B_1=17.7, C_1=0.3392, a=6.3×10-88, b=34.08. It can be seen from above formula, the fitting characteristic parameters R_g, R_1 and the temperature exhibit an exponential function, R_3 and the temperature exhibit a power function. Therefore, the change of temperature can reflect the variation law of the insulation resistance and the maximum and minimum time constant branch circuit

resistance in the extended Debye model. It is shown that the extracted characteristic parameters can be used to evaluate the influence of temperature on the oil - paper insulation. The quantity relationships of equation (3), equation (4) and equation (5) show that the effect of temperature on FDS test results is significant. Therefore, the FDS test process must take into account the impact of temperature, it's necessary to ensure the same test temperature in assessing moisture content and aging state of the oil-paper insulation bushing.

5. Conclusion

In this paper, the FDS test results of oil-paper insulation of the bushing at different temperatures are analysed and studied, and the following conclusions are drawn:

1) At different test temperatures, ε' and ε'' tend to move in the high frequency with the increase of temperature. ε' is substantially free from temperature in the high frequency range.

2) Complex capacitance measured curve of Oil-paper insulation of the bushing and 3 branch Debye dielectric response function model show a good fitting effect. The fitting characteristic parameters R_g, R_1 and the temperature exhibit an exponential function, R_3 and the temperature exhibit a power function. These functional equations can be used to evaluate the influence of temperature on the FDS of the oil-paper insulation bushing.

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