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Experimental Study and XY Model Simulation on the Polarization and Depolarization Characteristics of Oil-paper Insulation

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Abstract. In order to use polarization and depolarization current to diagnose the insulation statement of power transformer oil-paper composite insulation on site, XY conductivity model is put forward and deduced, and the test value of polarization current and depolarization current is used to verify the effectiveness of time domain XY conductivity model with different geometry in simulating the polarization and depolarization characteristic of oil-paper composite insulation, and to analyze the change rule of polarization and depolarization characteristic of oil-paper composite insulation. The results show that XY conductivity model is effective to simulate polarization and depolarization characteristic of oil-paper composite insulation with different geometry. Change of X has a greater influence on polarization and depolarization characteristic of oil-paper composite insulation than change of Y much more. With increasing of X and Y, variation trend of polarization current of oil-paper composite insulation changes little and amplitude decreases, and initial amplitude and rate of descent of depolarization current decreases and curve flattens out.

Keywords: XY conductivity model, polarization and depolarization current; polarization conductivity, geometry, temperature.

1. Introduction

Oil-paper insulation is the main part of the inner insulation of oil-immersed transformer. The insulation performance of oil-paper insulation determines the operating life of the transformer. Therefore, it is very necessary to explore the effective method for monitoring the insulation performance of oil-paper insulation [1].

For the shortcomings of traditional diagnostic method of the insulation performance of oil-paper insulation, many scholars put forward non-destructive diagnostic techniques based on the dielectric response. The polarization and depolarization current method attracts the attention of researchers since it can reduce measurement time and do not need hang on the transformer cover. Malaysian scholar N.A.M. Jamail studied the influence of electrical conductivity of solid and liquid dielectric material to its polarization and depolarization characteristics, and considered that the polarization and depolarization method can reflect the conductivity characteristics of high-voltage insulating materials very well[2]. Gafvert and other researchers first proposed the XY model, and proposed the application of the equation using in the frequency domain[3]. Chongqing University scholar Wen Hua and others simulated the application of XY model in the frequency domain, and the simulation results show that the simulation curve of XY model can better coincide with the frequency domain dielectric spectroscopy test curve of transformer model[4]. However, the study of description of the application of the equation using in the time domain and using the equation of XY model in the time domain to analyze the polarization and depolarization characteristics of oil-paper insulation is relatively scarce. In order to use polarization and depolarization current method to effectively assess the insulation state of oil-paper insulation, it is very necessary to deduce the theory of the time domain conductivity model of XY model and verify its effectiveness for analyzing the polarization and depolarization characteristics of oil-paper insulation.

In this paper, the conductivity expression of XY model in time domain for oil-paper insulation is proposed and deduced. The effectiveness of the conductivity expression of XY model in time domain is verified for simulating the polarization and depolarization characteristics of oil-paper insulation by experiment with the changing of geometry. The changing rule of the polarization and depolarization characteristics of oil-paper insulation is analyzed with the changing of geometry.

2. Experimental Schematic and Theory of XY Conductivity Model

2.1 Principle of Polarization and Depolarization Current Method

$$U(t)=\begin{cases}0 & t<0\\ U_0 & 0\le t\le t_s\\ 0 & t>t_s\end{cases}$$

(1)

According to the dielectric response principle of the dielectric, if the sample is applied to a voltage of (1), the test current through the sample will be zero before t=0. The test current is polarization current between t=0 and t=ts, which is composed by conduction current and displacement current and can be expressed as:

$$i_p(t)=C_0 U_0\left[\frac{\sigma}{\varepsilon_0\varepsilon_r}+f(t)\right]$$

(2)

where C_0 is the geometry capacitance of the dielectric, σ is the DC conductivity of oil-paper insulation, ε_0 is the vacuum dielectric constant, ε_r is the relative dielectric constant of the dielectric, f(t) is the dielectric response function. The voltage across the sample is zero after $t=t_s$, then if the two ends of the test sample is short-circuited, the depolarization current can be obtained by testing, and it can be expressed as:

$$i_d(t)=C_0 U_0\left[f(t)-f(t+t_s)\right]$$

(3)

2.2 Simulation Theory of XY Conductivity Model

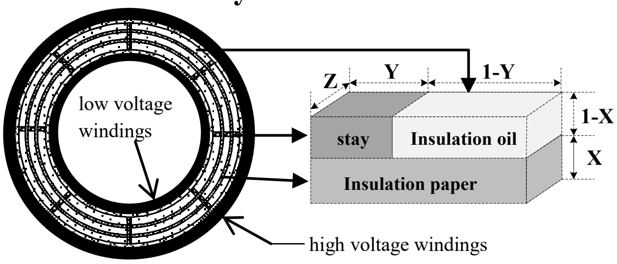

Fig. 1 XY model of the transformer internal main insulation system

Inside the transformer, the oil gap, stays and thin paper tube together make up the vertical oil passage between the high and low voltage windings and between phase and phase winding. They constitute the main insulation among the windings. According to the topology, the composite dielectric between the high and low voltage windings can be simplified to the structure copied by the units of oil clearance, stays and bulkhead, which is shown in the left part of Fig. 1. Each geometric unit is simplified to the structure shown in the right part of Fig. 1. Here the XY model is considered the simplified structure of the main insulation of actual transformer. Although the simplified model does not match with the actual situation in the appearance, the actual structure of transformer main insulation is the arc-shaped while the simplified model is the flat-shaped, the flat electrode using to test the polarization and depolarization characteristics makes up the deficiencies of this model in the shape. Because the electric field in the model is the same to the actual electric field in the transformer main insulation, both of them are exerted along the vertical direction of the cardboard. Thus, the XY model can be used as a simplified structure model of transformer main insulation during the polarization and depolarization characteristics is testing. X, Y is calculated as follows:

$$\begin{cases}X=k_1 d/D\\ Y=2k_2 l/(L_1+L_2)\end{cases}$$

(4)

Where k_1 is the total amount of bulkhead between high and low voltage windings, d is the thickness of each bulkhead, D is the thickness of main insulation between the high and low voltage windings, k_2 is the total amount of stays between two adjacent cardboard, l is the width of a single stay, L_1 is the perimeter of cardboard near the high voltage winding, L_2 is the perimeter of cardboard near the low voltage winding. For different geometries of oil-immersed transformers, X value is 0.2~0.5, and Y value is 0.1～0.3. The value of X and Y can be accurately calculated according to the insulation structure parameters of transformers.

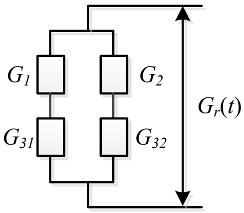

Fig. 2 Equivalent circuit of the XY model

For the XY model shown in Fig. 1, if the conductivity of the stay were G_1, the conductivity of the insulating oil were G_2, the conductivity of the left part cardboard under the stay were G_{31}, the conductivity of the right part cardboard under the insulating oil were G_{32}, then its equivalent circuit is shown in Fig. 2, where Gr is the composite conductivity of oil-paper insulation. Known by equation G=σS/l, the series branch conductance composed of G_1 and G_{31} is

$$G_{S1}=\frac{G_1G_{31}}{G_1+G_{31}}=\frac{YZ}{\frac{1-X}{\sigma_{stay}}+\frac{X}{\sigma_{paper}}}$$

(5)

The series branch conductance composed of G_2 and G_{32} is

$$G_{S2}=\frac{G_2G_{32}}{G_2+G_{32}}=\frac{(1-YZ)}{\frac{1-X}{\sigma_{stay}}+\frac{X}{\sigma_{paper}}}$$

(6)

The composite conductance of oil-paper insulation is

$$G_r=G_{S1}+G_{S2}=\frac{YZ}{\frac{1-X}{\sigma_{stay}}+\frac{X}{\sigma_{paper}}}+\frac{(1-YZ)}{\frac{1-X}{\sigma_{oil}}+\frac{X}{\sigma_{paper}}}$$

(7)

The composite conductivity of oil-paper insulation is

$$\sigma_r=\frac{Y}{\frac{1-X}{\sigma_{stay}}+\frac{X}{\sigma_{paper}}}+\frac{1-Y}{\frac{1-X}{\sigma_{oil}}+\frac{X}{\sigma_{paper}}}$$

(8)

Considering that it is the laminated cardboard that always be used in actual transformer, and the conductivity of laminated cardboard can be assumed the same as the conductivity of the paperboard used for paper roll, thus, the equation (8) can be simplified as:

$$\sigma_r=\sigma_{paper}Y+\frac{1-Y}{\frac{1-X}{\sigma_{oil}}+\frac{X}{\sigma_{paper}}}$$

(9)

The polarization current of oil-paper insulation can be deduced by its polarization conductivity as shown in the following equation:

$$i_p(t)=\sigma_r(t)\frac{U_0S}{l}$$

(10)

By (10), the polarization current of oil-paper insulation based on the XY conductivity model can be calculated. Then the dielectric response curve of oil-paper insulation can be obtained using (2).

The fitted values of the unknown parameters in the function expression of the dielectric response can be obtained by least-squares fitting to the dielectric response curve of oil-paper insulation according to (11). Substituting the fitting dielectric response function *f*(*t*) into (3), the simulation value of depolarization current *id*(*t*) can be obtained.

$$f(t)=\frac{A}{\left(\frac{t}{t_0}\right)^m+\left(\frac{t}{t_0}\right)^n} \tag{11}$$

Where the parameters are met: A>0， t0>0， m>n>0， m>1.

3. Experimental Test for Polarization and Depolarization Current

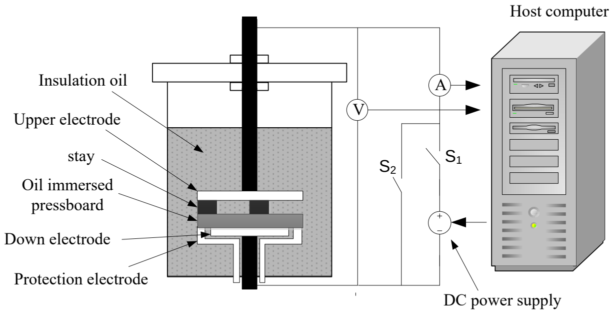

Fig. 3 Test circuit for Polarization and depolarization current

The ordinary transformer insulating kraft paper (thickness of 0.3mm) and 25# mineral insulating oil are used as experimental material. The experimental platform as showing in Fig. 3 is built for experimental test. The test charging voltage is 200V, and the charging time is 10^4s. The insulation pressboard and stays are placed between two electrodes and immersed in the insulating oil. In the test, the width of stays are changed depending on the X value, the width of pressboards are changed depending on the Y value. In order to eliminate edge effects, the protective electrode is added. The whole test device is placed in a temperature control box to control the temperature of the experiment.

4. Test Results and Analysis

4.1 Test Results for the Conductivity of Insulating Oil and Insulation Paper under 30°C

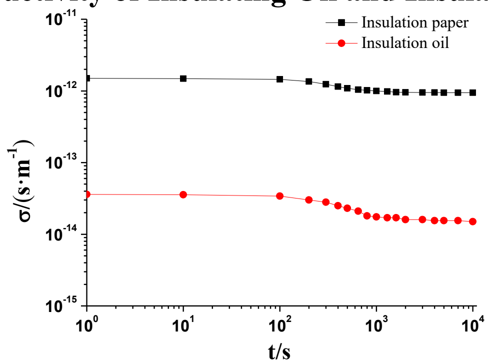

Fig. 4 Polarization conductivity of insulation oil and insulation paper at 30°C

The polarization conductivities of both insulation oil and insulation paper are measured at 30℃ using the measuring device shown in Fig.3, and the measuring results are shown in Fig.4. It can be seen from Fig.4 that the declining rate of the polarization conductivity of both insulation oil and insulation paper becomes larger near 400s, and essentially does not change after 1000s.

4.2 Effectiveness Analysis for Using XY Conductivity Model to Simulate the Polarization Characteristics of Oil-paper Insulation with Different Geometry

The geometry of Oil-paper insulation varies from the change of the voltage level and the transformer capacity [5]. In order to study the effectiveness of XY conductivity model to simulate the polarization characteristics of oil-paper insulation with its geometry changing, the geometrical structures of the sample are divided into four categories, which respectively are X=0.2, Y = 0.15; X=0.2, Y=0.25; X=0.4, Y=0.15; X=0.4, Y=0.25. Fig. 5 shows the XY conductivity model simulation values and fitting curve of the polarization conductivity of the oil-paper insulation with four different geometries under 30℃. By (10), the XY conductivity model simulation curve of oil-paper insulation polarization current can be attained. The testing values of polarization current and XY conductivity model simulation curve of the polarization current are as shown in Fig. 6. It can seen from the figure that the polarization current value of the oil-paper insulation calculated by the XY conductivity model has a good agreement with the actual measured value, and the change of geometry has little influence on the trends of the polarization conductivity and current of the oil-paper insulation, but has a huge impact on the amplitudes of both factors. When the X value increases, the amplitudes of both factors decline by a big margin. When Y increases, the amplitudes of both factors also have a downward trend, but the decline range is not big.

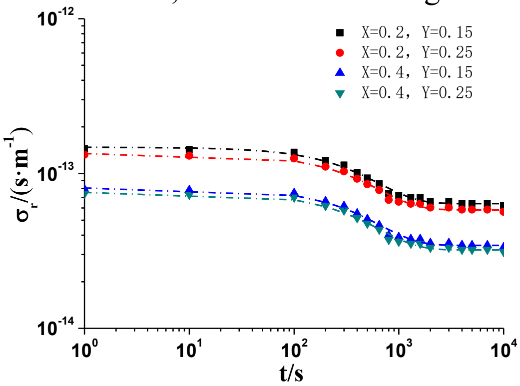

Fig. 5 Simulation value and fitting curve of the polarization conductivity curve of oil-paper composite insulation with different XY value

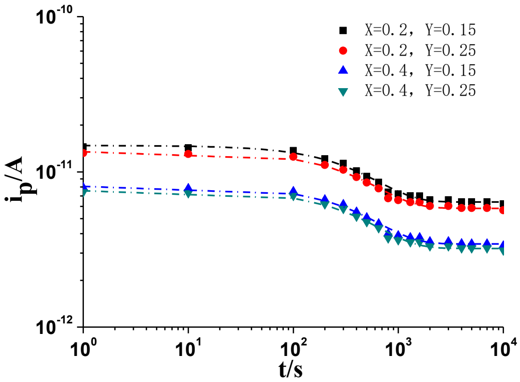

Fig. 6 Test value and simulation curve of polarization current of oil-paper composite insulation with different XY value

4.3 Effectiveness Analysis for Using XY Conductivity Model to Simulate the Depolarization Characteristics of Oil-paper Insulation with Different Geometry

The dc conductivity testing values of the oil-paper insulation with different geometries under 30℃ are as shown in the Table 1. Substituting the XY conductivity model simulation values of the oil-paper insulation polarization conductivity under 30℃ into (10), the XY conductivity model simulation values of the oil-paper insulation polarization current under corresponding conditions can be calculated. Then substitute the attained simulation values of polarization current and the corresponding testing values of dc conductivity into (2), thus the XY conductivity model simulation values of dielectric response of oil-paper insulation can be obtained shown in Fig. 7. The least-square fitting over the XY conductivity model simulation values of dielectric response of oil-paper insulation is made using the function expressed in (11), and the parameters fitted values and goodness of fitting are shown in Table 2.

Table 1 Dc conductivity of oil-paper composite insulationwith different XY value

X,Y value	0.2,0.15	0.2,0.25	0.4,0.15	0.4,0.25
σ_{rD}/s·m^{-1}	7.44×10^{-15}	5.63×10^{-15}	1.57×10^{-15}	9.85×10^{-16}

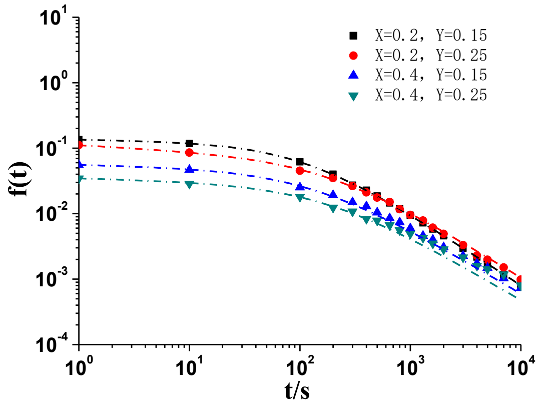

Fig. 7 Simulation value and fitting curve of dielectric response curve of oil-paper composite insulationwith different XY value

Table 2 Parameters fitted values and goodness of fitting for dielectric response function of oil-paper composite insulation with different XY value

X,Y value	A	t_0	n	m	R^2
0.2,0.15	0.1177	108.6	0.0306	1.102	0.9998
0.2,0.25	0.0685	189.7	0.0938	1.049	0.9993
0.4,0.15	0.0463	130.8	0.0390	1.001	0.9969
0.4,0.25	0.0276	176.1	0.0454	1.001	0.9942

Substitute the dielectric response function $f(t)$ achieved by fitting into (3), and the XY conductivity model simulation curve of the oil-paper insulation depolarization current can be calculated. The comparison results between the simulation curve and the testing values of the oil-paper insulation depolarization current are as shown in Fig. 8. It can be seen from the figure that the simulation curve matches well with the testing values. Changes of X and Y values both have a great influence on the polarization characteristics of oil-paper insulation and the impact caused by the change of X value embodies much more degree than the change of Y value. With the increase of X and Y values, the initial amplitudes of the depolarization current curves of oil-paper insulation all decrease, and the declining rates all reduce. The curve becomes more and more gentle and the depolarization current curves of the oil-paper composite insulation with different geometries intersect near 600s.

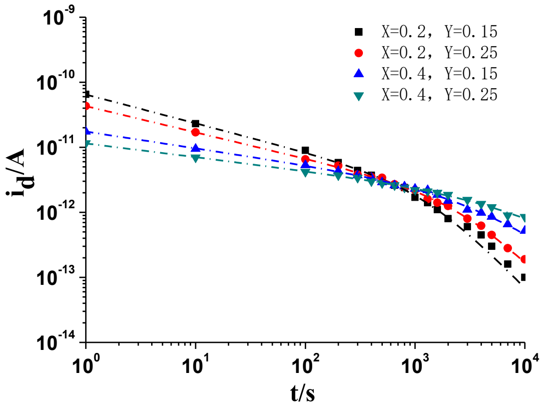

Fig. 8 Depolarization current test value and simulation curve of oil-paper composite insulation with different XY value

5. Conclusion

1) XY conductivity model is put forward and deduced, and the simulation values of oil-paper insulation polarization and depolarization current match well with the test value in dif ferent geometries.

2) Changes of X and Y values both have a great influence on the polarization characteristics of oil-paper insulation and the impact caused by the change of X value embodies much more degree than the change of Y value.

3) The increasing of X and Y values both lead to the decreasing of the amplitude of the polarization current and the initial amplitudes of the depolarization current curves of oil-paper insulation, and the declining rates all reduce. The curve becomes more and more gentle and the depolarization current curves of the oil-paper composite insulation with different geometries intersect near 600s.

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