A Study on the Relaxation Function and Moisture of Oil-Paper Insulation in Transformers Based on Frequency Domain Spectrum

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***Abstract* — The frequency domain spectrum provides a different method for estimating the ageing state and the moisture content of oil-paper insulation of a transformer. In order to analyze the relationships between a dielectric spectrum of an oil-paper insulation system and frequency, and between the dielectric spectrum and moisture, an experimental device is built in the laboratory. The influence rule and mechanism of moisture on a main insulation system of the transformer are studied and determined through the inverse Fourier function to obtain the relaxation function of a combination insulation system. The results show that the relaxation function containing three relaxation terms is more suitable for a three-phase system of the oil-paper insulation system with moisture.**

Keywords — moisture; oil-paper insulation; frequency domain spectrum; relaxation function

I. ITRODUCTION

Oil-paper combination insulation (transformer oil and an insulating paper board) is a main insulation system of an oil-immersed transformer, the moisture (also called "free water"), suspended in the oil-paper combination insulation, severely impairs the insulating property of the transformer, and thus the stability [1-2] of a power system is influenced. Therefore, determination of the moisture content in the transformer is always an important subject of studies of domestic and foreign scholars. Due to tedious testing process, the traditional measuring method is larger in error of measuring result and is gradually replaced by a new testing method[2]. Since the 1990s, as a new insulation testing method, a dielectric response method can particularly realize non-destructive diagnosis of the transformer and is widely studied. The frequency domain spectrum (FDS) is one of them. The method is slow polarization response under the action of an alternating current field, is strong in anti-jamming capability due to narrow measuring bandwidth and is more and more widely studied [3-4]. The insulation system of the transformer is a complex multiphase insulation system which brings difficulty to construction of model, and a Debye model, a Cole-Cole model and the like in the dielectric theory also have their own limitation although being generally applied in test result analysis.

For example, the Debye model is mainly applied to dielectric spectra of polar liquid and solid dielectrics, only suitable for a single-phase insulation system and equivalent to a loop consisting of an RC circuit in parallel connection and a plurality of RC circuits in series connection[5]. To get a frequency domain analysis method with a wider range, an expression of the relaxation function must be obtained firstly. But, the relaxation function is relevant to factors including ingredients and structures of matters and environment temperature, and therefore, a common expression which can be applied to various places is difficult to find[6]. Fourier transformation can decompose an arbitrary real periodic function into a sum of sinusoidal signals with higher and higher frequency domain. Therefore, with utilization of this advantage of the Fourier transformation, the expression of the relaxation function is get through curve fitting and inverse Fourier transformation.

This paper tests dielectric response of the oil-paper insulation system under the conditions with different moisture contents and within a frequency range of 10-4-105 Hz, focuses on studying the inside mechanism of the moisture of influencing the oil-paper insulation system and utilizes a fitting method to obtain the relaxation function.

II. BASIC THEORY OF FREQUENCY DOMAIN SPECTRUM

As shown in Figure 1, a sine voltage signal E (t) is applied to the two ends of a plate capacitor C_0, and the relaxation process can generate in the dielectric under the stimulation of the alternating current field. A total current, passing through the dielectric, is composed of three parts, namely an transient charging current, an absorption current and a leakage conductance current. A time-domain method used for the total current is expressed as follows[6]:

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The current density solved by the Maxwell equation is as follows:

$$j(t) = (\varepsilon_s - \varepsilon_\infty)\int_0^\infty \frac{dE(t-x)}{dt}\varphi(x)dx + \varepsilon_\infty \frac{dE(t)}{dt} + \gamma \dot{E}(t)$$

(2)

Enabling $\dot{E} = E_0 e^{i\omega t}$ without considering the influence of the density $\gamma\dot{E}(t)$ of the leakage conductance current, then the equation is as follows:

$$i\omega(\varepsilon_s - \varepsilon_1)\dot{E}\int_0^\infty \varphi(t)e^{i\omega t}dt + i\omega\varepsilon_\infty\dot{E}$$

$$i\omega\dot{E}\left\{\varepsilon_\infty + (\varepsilon_s - \varepsilon_\infty)\int_0^\infty \varphi(t)\cos\omega t\,dt\right\} +$$

$$\omega\dot{E}(\varepsilon_s - \varepsilon_\infty)\int_0^\infty \varphi(t)\sin\omega t\,dt \quad (3)$$

The current density can also be expressed by a formula (4):

$$j = i\omega\varepsilon^*\dot{E} = (i\omega\varepsilon' + \omega\varepsilon'')\dot{E} \quad (4)$$

Comparing the formula (3) and the formula (4), following formulas can be obtained:

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Where in ε_s is a static relative dielectric constant, ε_1 is an optical frequency dielectric constant, and ε' and ε'' are respectively a real part and an imaginary part of a complex dielectric constant, wherein the real part represents a dielectric constant of a material, and the imaginary part represents dielectric loss of the material. $\varphi(t)$ is time domain expression of the relaxation function, and the real part and the imaginary part of the complex dielectric constant both depend on the relaxation function. Test parameters in the frequency domain can be transformed in the time domain by utilizing the inverse Fourier transformation or inverse Laplace transformation, and thus the expression of the relaxation function is obtained.

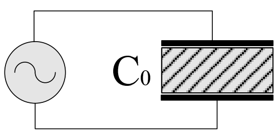

Fig.1 Plate capacitor filled with dielectric.

III. Experiment

A. *Experimental Material*

Insulation paper: 0.3mm common cellulose insulation paper

Insulation oil: 25# transformer oil/naphthenic group

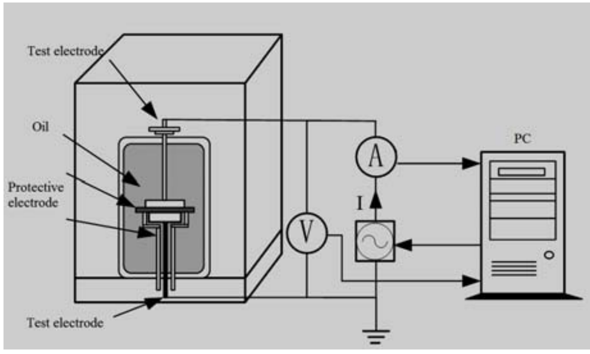

Fig.2 The experimental device

B. *Experimental Procedure*

The insulating paper board with the thickness to be 0.3mm is shorn into a square with the side length to be 140mm. The square is put into a "WD841-2" type electric heat oven and placed for 2-3 days under the condition with the constant temperature to be 120 DEG C to ensure the paper board sample to be completely dried. After drying, the sample is put in air (in the laboratory) to absorb the moisture, and simultaneously, four samples with the moisture contents respectively to be 0.98%, 2.03%, 3.11% and 4.16% are obtained by testing with utilization of Karl Fisher titration, then put in the transformer oil (the moisture content in the oil is 12ppm) to ensure the moisture in the oil-paper combination insulation to reach balance and then tested. A testing device is shown in Figure 2.

C. *Oil-paper Insulation Physical Model*

The oil-paper insulation system of the transformer is a two-phase insulation system and can be seen as being composed of a plurality of capacitors and a resistor. If containing dissolved "free water", the oil-paper insulation system can be seen as an equivalent three-phase insulation system model, shown in Figure 3. Seen from the model, the insulation system is described by a series equivalent loop of three [C-G] loop units. Using a deducing method of the Debye relaxation equation as a reference, the insulation system can be considered to contain three relaxation items, and the relaxation function of the insulation system is:

$$\varphi(t) = a_1 * e^{-b_1 t} + a_2 * e^{-b_2 t} + a_3 * e^{-b_3 t},$$

and parameters for reflecting the interior properties of the system are obtained by fitting the dielectric spectrum of the relaxation function with utilization of the Fourier transformation and then through inverse Fourier transformation.

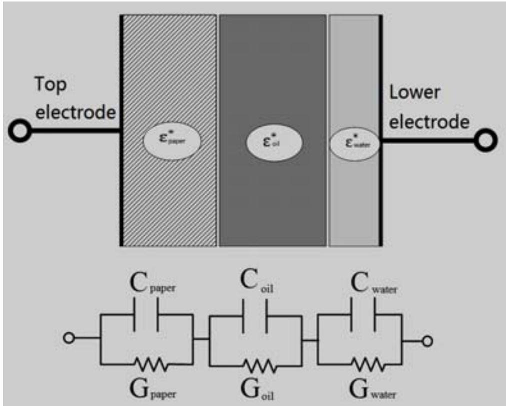

Fig.3 The equivalent three-phase insulation system model of oil, paper and water.

IV. TEST RESULT AND ANALYSIS

A. Influence Mechanism of Moisture Content on Main Insulation

The moisture content is one of important factors of deciding the service life of the transformer, moisture can not only accelerate ageing of the oil-paper insulation system and is also a product of ageing, and the influence is more obvious particularly when oil contains fiber impurities [2]. In order to study frequency response of oil-paper combination insulation at different moisture contents, the dielectric spectra of the oil-paper combination insulation at the moisture contents respectively to be 0.98%, 2.03%, 3.11% and 4.16% at 25 DEG C are tested. Test results are shown in Figure 4 and 5.

Figure 4 indicates that within a range of 10^{-4}-10^{2}Hz, the real part ε' of the complex dielectric constant of the oil-paper combination insulation is increased along with the increase of the moisture content. The reason may be that the transformer oil is of nonpolar molecules, polarization of the nonpolar molecules mainly depends on electron displacement polarization, while the establishment time of the electron displacement polarization is very short (to be about10^{-16}-10^{-12}s), so the dielectric constant of the transformer oil can be approximately a constant value. But the moisture is of polar molecules and is difficulty dissolved in the transformer oil according to the "similarity-inter-miscibility theory", so water molecules near the surface of the transformer oil can deform caused by constraint, resulting in increase of the dielectric constant, and the higher the "free water" constant is, the larger the dielectric constant is. While within the range of 10^{2}-10^{5}Hz, ε' of the oil-paper combination insulation does not obviously change any more along with the change of the moisture content. The reason may be that relaxation polarization time of the moisture is equivalent to the period of the alternating current field at this moment, the polarization lag effect also occurs on polarization of the polar molecules, orientation of dipoles cannot catch up on change of an electric field, and therefore, polarization is little influenced by the moisture content at this moment.

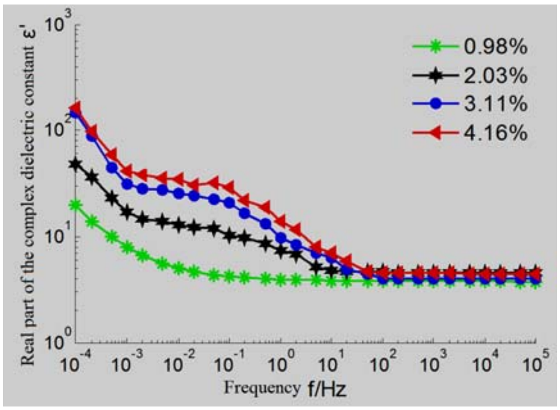

Fig.4 Real part of the complex dielectric constant at different moisture contents at 25℃

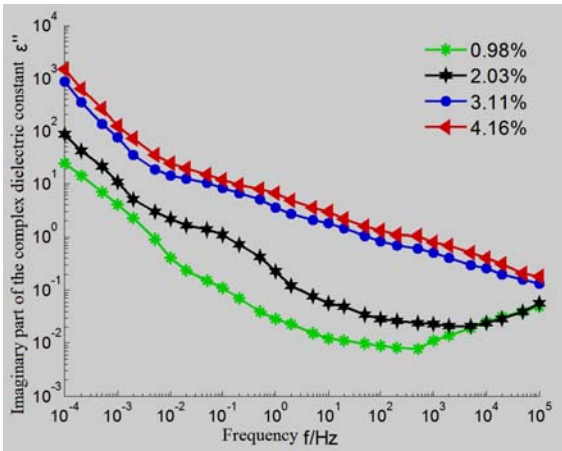

Fig.5 Imaginary part of the complex dielectric constant at different moisture contents at 25℃

Figure 5 indicates that within a range of 10^{-4}-10^{3}Hz, ε'' of the oil-paper combination insulation is increased along with the increase of the moisture content. The reason is that the moisture contains more conductive ions, and the higher the moisture content is, the larger the amount of impurity in the oil-paper insulation system is, so that conduction of insulation is improved, current, flowing through, is increased, and the loss is also larger. While after 10^{3}Hz, as the frequency of the electric field is rapider, motion of ions has not catch up the change of the electric field already and is little relevant to the moisture content.

It can be seen from the Figure 4 and the Figure 5 that the dielectric spectrum of the insulation system shows a trend of moving towards the low frequency direction. Along with the increase of the moisture content, the difference between ε' and ε'' is smaller and smaller, and this shows that the moisture reaches the "saturation" state and is not obvious in influencing the insulation system any more. The reason may be that the water molecules with very small particle radius are distributed in the insulation oil with very low conductivity, and conduction of the whole system are from contributions of two parts, including electrophoresis conductivity (motion of charged particles under the electric field) and ionic conductivity (migration motion of free ions in the dielectric). When the concentration reaches a certain degree, the contribution of the ionic conductivity has not been obvious yet relatively, while, the value of the electrophoresis conductivity is very small and can be considered to be a constant value, and therefore, the influence of the moisture is smaller and smaller.

B. Relaxation Function Analysis

Curve fitting is respectively carried out on the real part and the imaginary part of the complex dielectric constant by utilizing the Fourier transformation, then the expression of the relaxation function is obtained through the inverse Fourier transformation, and each parameter value in the relaxation expression is shown in Table 1. The relaxation function is introduced into the formula (5) and the formula (6), and the complex dielectric constant is transformed in the frequency domain to obtain a curve, shown in the Figure 6. Seen from the figure, the curve is very good in anastomosing with test data. Therefore, the relaxation function, assumed according to a model of the three-phase equivalent insulation system model of oil, paper and water, is reasonable. Meanwhile, the parameters a_1, a_2 and a_3 can represent reciprocals of relaxation time, and thus increase of the needed relaxation time along with the increase of the moisture content due to enhancement of dielectric polarization can be obtained.

TABLE I. PARAMETER VALUES OF RELAXATION FUNCTION

Moisture	a_1	b_1	a_2	b_2	a_3	b_3	R^2
0.98%	0.05793	1.401	0.006251	2.372	15.24	0.01156	0.9936
2.03%	0.02368	1.808	0.001638	2.215	11.64	0.1427	0.9961
3.11%	0.001172	2.852	0.0000579	3.092	7.754	0.3278	0.9954
4.26%	0.000221	3.257	0.0000317	2.938	3.909	0.2705	0.9933

V. CONCLUSION

(1) The real part and the imaginary part of the complex dielectric constant of the oil-paper insulation system are both increased along with the increase of the moisture content and wholly show a trend of moving towards the low frequency direction.

(2) There is a limit for influence of the moisture on the complex dielectric constant of the oil-paper insulation system, and the moisture cannot obviously influence the insulation system when the moisture content reaches a certain concentration.

(3) The relaxation function containing three relaxation items is more suitable for the oil-paper insulation system containing the moisture, and in addition, the relaxation times shows a gradually increasing trend along with the increase of the moisture content.

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