Application of Time-Frequency Domain Combined Medium Response Technology in the Insulation Moisture Evaluation of Transformer Oil-Paper

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Abstract. In the current period, many transformers in domestic power supply departments are in the state of overdue service, there are many problems of insulation aging and increasing water in the body, and the rapid and accurate insulation moisture assessment is a technical problem that needs to be solved. The commonly used methods of medium response test for damp evaluation of transformer oil-paper insulation system include time-domain PDC and frequency-domain FDS. These two methods have their own advantages, but also have their own disadvantages. The purpose of this paper is to transform these two test methods into time-frequency combined medium response technology combining time-domain PDC method and frequency-domain FDS method, which can be used in transformer oil paper insulation moisture evaluation to improve the efficiency of transformer operation detection. In this paper, PDC method, FDS method and time-frequency combination method were used to obtain the response curves of insulating oils with different water contents, and the curves were analyzed. By comparing the results of measuring time and water content, the effectiveness of time-frequency combination method was verified. The experimental results of this paper further show that the time-frequency domain combined media response technology has a good application value in the evaluation of transformer oil paper insulation damp.

Keywords: Medium Response, Oil-Paper Insulation, Time-Frequency Combination, Potential Transformer

1. Introduction
During the operation of the transformer, the oil-paper insulation system is subject to the effects of electric field, moisture and temperature for a long time, resulting in the qualitative change of the power supply system. Among them, the moisture content in oil-paper insulation is an important factor affecting the service life of transformers. Under normal circumstances, every doubling of the moisture in the oil-paper insulator of the transformer will reduce the overall service life of the transformer by half. On the one hand, this is because the water in the oil paper insulation heated by the bubble will become the insulation of the hole, resulting in local unprovoked discharge; On the other hand, these
moisture will also accelerate the aging of oil paper, and the aging process will further produce new moisture to accelerate the aging process. Therefore, it is of great significance to study the damp degree of transformer oil-paper insulation for the safe operation of voltage generator.

At present, there are two main methods to evaluate the insulation moisture of transformer oil paper at home and abroad. Another is the transformer solid insulation material performance testing. Conventional methods for electrical detection include frequency spectrum analysis (FDS), frequency domain analysis (FDS), Karl fischer titration, and time-frequency conversion methods commonly used at present [1, 2]. The most intuitive method to judge the damp state of transformer oil-paper insulation is to measure the degree of polymerization, but this method has great limitations, because it can only be used in the process of transformer core lifting [3]. The Karl fischer titration method can be used to measure moisture content in the insulation of transformer oil paper, and then approximate moisture content of solid insulation can be obtained according to the normal oil-water balance relationship [4]. However, the water transfer of transformers is often very complicated, and it takes a long time for oil-paper water transfer to be observed at different temperatures [5].

It can be seen that the existing research methods at home and abroad have certain limitations. Different from the existing research methods, this paper intends to adopt a combination of time domain analysis and frequency domain analysis. This method first measures the moisture in insulating oil of transformer oil paper, and then predicts the moisture degree of insulating oil paper according to the moisture balance of oil paper [6]. The method in practice measure belt width, the advantages of strong anti-jamming capability, the research of this paper adopts the method of different temperature and moisture content of the paper to study the dielectric properties, concludes the different temperature insulation paper moisture content and the relationship between the dielectric spectrum characteristics, and on the dielectric loss factor of different temperature normalized processing, to eliminate temperature influence on frequency domain dielectric properties of insulating paper [7, 8]. Considering the need of the electric field in the direct current of the converter, as well as the requirement of more accurate reflection of the current damp degree of the transformer equipment, this paper also adopted the polarization current method to test and study the water content and oil-immersed conductivity at different temperatures, and carried out fitting analysis on the test results [9].

2. Method

2.1 Theoretical Basis
In the frequency domain analysis was carried out on the sample, can be measured by the corresponding frequency response under the current phase and amplitude, and change with the frequency of the excitation voltage, and the repair insulating medium is the change of the relationship between capacitance and dielectric loss factor, the relationship between the parameters and oiled paper insulation system is closely related to the degree of water content, wreck on the relationship (10 to 11). Then, according to the dielectric theory, the variation relationship of these parameters with temperature and frequency can be analyzed, so as to realize accurate judgment of the insulation state of the transformer [10-12].

The permeability of oil-paper at different temperatures was measured by polarization current method. The principle basis of the test can be expressed as: apply a dc voltage to the sample, charge continuously and keep the polarization current stable, then conduct a short discharge at the sample end of the test, and record the depolarization current during the discharge process. By comparing the depolarizing current with the initial value and the final value, the amplitude space of the current curve is described to realize the influence of the moisture content in the oil-paper insulator on the conductivity.

2.2 Oil-Paper Insulation Model
Oil paper insulator is composed of insulating oil, insulating paper and bracing. Among them, the high
voltage winding is in the outermost side, and the low voltage wire set is wound in the outermost side. In addition, the support function of the pad is played by the winding of multi-layer insulating oil paper, so the mechanical strength of the whole insulation system is greatly enhanced. When the entire insulation system is completely immersed in the transformer, the gaps between the oil sheets are filled with transformer oil. The oil-paper insulation system is housed inside the transformer's case and is filled with insulating oil. The elimination of air also enhances the insulation of the transformer.

Debye model is an equivalent circuit model derived from the theory of dielectric. In the theoretical research experience of electrolyte, the two parallel plates are usually regarded as the important characteristic properties of electrolyte, and the middle plate is filled with a single dielectric. The electrode area is $S$, and the distance between the two plates is $l$. When charging the capacitor, the total electric load on the plate is $Q$. When there is no other material between the electrolytes, the electric field is expressed as $E$, so the electric displacement $D$ and electric field $E$ of the plate capacitor are respectively:

$$D = \varepsilon_0E_0 = \frac{Q}{S}$$  \hspace{1cm} (1)

$$E = \frac{D}{\varepsilon_0} = \frac{E_0}{\varepsilon}$$ \hspace{1cm} (2)

Where, $\varepsilon$ is the filling electrolyte electrolysis parameter, and $0$ is the medium parameter in the vacuum state. Electrolyte is heterogeneous in the process of polarization, and a single capacitance model may not be able to accurately describe the polarization state of electrolyte. Therefore, a series of resistors and capacitors is adopted to simulate the polarization of insulating materials. The structure of oil-paper insulation system is relatively complex, and the dielectric parameters of insulating oil and insulating paper are different, so their characteristics during the polarization process are inevitably difficult to keep consistent.

The polarization reaction of substances is expressed by the dielectric constant and frequency. In the applied field, the relation between the dielectric constant and frequency can be expressed as follows:

$$\varepsilon(\omega) = \varepsilon_\infty + \int_0^\infty a(t)e^{i\omega t}dt$$ \hspace{1cm} (3)

Where, $a(t)$ is the weak factor, which represents the instantaneous removal of polarization inertia of the dielectric under the action of external electric field. Because of the delay of the moment motion, the polarization instability of the electric field will be enhanced. In the process of polarization, the electrolyte will exchange energy with the surrounding particles, which is shown as energy consumption in the macroscopic theory.

3. Experiment

3.1 Experimental Materials and Preparation

In this experiment, oil-immersed paper is used to analyze the converter transformer. The X150KA transformer and T4 board were selected as the samples in the experiment, which is based on the consideration that these two materials have been very mature in the practical converter transformer application. The transformer oil was dehydrated by vacuum oil filter according to IES38942 standard.

After the treatment, the water content of transformer oil is guaranteed to be less than 81/L, and the breakdown voltage under 3mm gap is greater than 120kV. The insulating board with a thickness of 0.9mm is processed into wafers, which are dried in an oven at 75Pa/100°C for 24h. Then, the dried samples are exposed to the air. The moisture quality of transformer oil and oil-immersed paper samples was measured by moisture meter, and the water content of the four samples was 0.72%, 1.17%, 1.64% and 2.25%, respectively.
3.2 Experimental Process
The experiment consists of three electrodes, oven and test instrument. The test instruments selected in the experiment have the functions of FDS and PDC. The oil-immersed paper samples were tested at 20°C, 40°C, 60°C and 80°C respectively. During the frequency-domain spectrum test of the samples, the samples were located in three liquid electrodes filled with transformer oil, the experimental voltage was stabilized at 500V, and the spectrum was adjusted at 10^3hz ~10^5Hz. The polarization depolarization current was tested by electrometer 5375B with a test voltage of 500V and a duration of 150min.

4. Discuss

4.1 Response Curve and Moisture Analysis
The following is the result of water content analysis of the three transformers by oil-immersed paper with the converter transformer. The medium response curve of the three transformers is shown in figure 1 below. The measured curve in the figure is the dielectric loss curve of each transformer at different temperatures. The model curve is the curve obtained by matching the measured curve with the aging model of the instrument software, and then compensating the transformer's shape, temperature and oil conduction number according to the built-in adaptation algorithm.

![Figure 1. Dielectric response curves of three transformers](image)

As can be seen from figure 1, tangent -f presents a typical inverse s-shaped curve. According to the actual measurement results, the water content of the three transformers is shown in table 1 below.

| Equipment    | Temperature / °C | Moisture content /% | Degree of dampness |
|--------------|------------------|---------------------|--------------------|
| No. 1 transformer | 22               | 1.8                 | Normal             |
| No. 2 transformer | 20               | 4.9                 | Severe             |
| No.3 transformer | 23               | 2.6                 | Moderate           |

According to IES38942, when the water content of the test transformer board is less than or equal to 2.3%, it is normal; when the water content is between 2.3% and 3.6%, it is medium humidity; and when the water content is greater than 3.6%, it is considered as severe humidity. It should be pointed out that, in this test, the oil bunker of no.2 transformer is open structure. Due to long-term exposure to air, water molecules will inevitably invade into the bunker from the bottom of the transformer, so the measurement results are worthy of caution. No. 3 transformer has been in service for a long time...
before the experiment, and its internal firmware is difficult to ensure that there is no aging factor, which will lead to the increase of fiber molecular chains and decomposition products contained in the insulating oil paper, thus leading to the increase of charged particles in the insulating oil paper. In addition, water molecules are conductive, so the dielectric loss of insulating oil paper in this experiment also has the factor of increasing consumption. It can be found from table 1 that the humidity level in no.1 transformer is in normal state. The test result of no. 2 transformer is extremely wet, but it is most likely caused by its open tank structure. The measuring result of no. 3 transformer is moderate humidity, which is also closely related to the longer service time, as mentioned above.

4.2 Comparison Between the Results of the Media Response Method and the Preventive test

The following table 2 shows the accurate results of water content of the low-voltage winding under the condition of power failure maintenance by adopting PDC method, FDS method and time-frequency combination method. From the table, it can be found that the time-frequency combination method is the most ideal in the dielectric loss test, and the time-frequency combination method can be used to evaluate the dielectric loss of oil-paper insulation equipment.

**Table 2. Comparison of processing results of PDC method, FDS method and time-frequency combination method**

| Equipment       | PDC       | FDS       | Time-frequency combination |
|-----------------|-----------|-----------|---------------------------|
|                 | Cx/nF     | tan8/%    | Cx/nF     | tan8/% | Cx/nF     | tan8/% |
| No.1 transformer| 9.235     | 0.817     | 8.362     | 0.757  | 2.189     | 0.163  |
| No.2 transformer| 4.252     | 0.573     | 5.243     | 0.624  | 1.634     | 0.124  |
| No.3 transformer| 8.352     | 0.781     | 8.921     | 0.793  | 2.074     | 0.161  |

Through these three detection methods, the testing results of the damp state of insulating oil paper for three transformer equipment show that the water content detected by time-frequency analysis method is consistent with the operating condition of the transformer. Then, through the testing of the fitting of the measurement curve, the damp state of insulating oil paper for the transformer can be detected and evaluated. Therefore, the combination of PDC method and FDS method for time-frequency analysis is a less time-consuming and very convenient detection method.

5. Conclusion

In this paper, extended debye model is used to describe the relaxation polarization process of dielectric response in detail, and a simulation curve is established to characterize the FDS curve. Based on the model, the effective method for evaluating the insulation moisture exposure of transformer oil-paper is discussed. This paper mainly draws the following two conclusions:

1. In addition to obtaining insulation information parameters, the time-frequency domain combined medium response technology can also extract the conductivity of insulating oil paper to evaluate the insulation moisture degree of transformer oil paper.

2. The medium response technology combined with time-frequency domain can avoid the adverse effect of human factors in the traditional method on the moisture evaluation in the oil-paper insulator of the transformer, and also solve the problem that the transformer in operation cannot extract the paper sample to test the water content.

At present, the time-frequency domain combined medium response technology is still in the initial stage of research and application. However, as a technology to evaluate the insulation moisture exposure of transformer oil paper, it has a good application prospect.

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References

[1] D. Mishra, N. Haque, A. Baral. Assessment of interfacial charge accumulation in oil-paper interface in transformer insulation from polarization-depolarization current measurements [J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2017, 24(3):1665-1673.

[2] Deba Kumar Mahanta, Shakuntala Laskar. Investigation of transformer oil breakdown using optical fiber as sensor [J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2018, 25(1):316-320.

[3] Zhifei YANG, Zhiye Du, Jiangjun Ruan. Simulation on motion characteristics of space charge in single oil-paper insulation [J]. Compel International Journal for Computation & Mathematics in Electrical & Electronic Engineering, 2017, 36(6):10-13.

[4] A.N. Nagashree, V. Champa, B.V. Sumangala. High Frequency Dielectric Properties of Insulation Systems with New Natural Vegetable Seed Oils [J]. Materials Today Proceedings, 2018, 5(1):2685-2695.

[5] Reza Rostaminia, Mohsen Saniei, Mehdi Vakilian. "An Efficient Partial Discharge Pattern Recognition Method Using Texture Analysis for Transformer Defect Models"[J]. International Transactions on Electrical Energy Systems, 2018, 3(1):12-13.

[6] Dai Jianzhuo, Yue Yonggang, Duan Changjun. Dielectric loss of transformer Oil-based nanofluids: Effects of Oil temperature and nanoparticle concentration [J]. Nanoscience & Nanotechnology Letters, 2017, 9(9):1298-1305.

[7] Deba Kumar Mahanta. Electrical Insulating Liquid: A Review [J]. Journal of Advanced Dielectrics, 2017, 07(4):1730001.

[8] Soumya Thakur, R. Sarathi, Ribhu Gautam. Thermal aging of cellulosic pressboard material and its surface discharge and chemical characterization [J]. Cellulose, 2017, 24(1):5197-5210.

[9] ZHENG Wendi, CAI Jinding, ZENG Jinglan. Aging Evaluation of Oil-Paper Insulation System Using Line Shape Factor [J]. Power System Technology, 2017, 474(429):1037-1042.

[10] N. Zhang, J. Cai. Evaluation of insulation state based on the combination of analytical hierarchy process and TOPSIS [J]. Yi Qi Yi Biao Xue Bao/Chinese Journal of Scientific Instrument, 2018, 39(11):35-42.

[11] B. X. Du, W. B. Zhu, X. L. Li. Effects of direct fluorination on charge coupling behavior of oil-paper insulation under DC and pulse voltages [J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2017, 24(2):947-955.

[12] Y. Wang, Z. Zhong, J. Xie. Influence of Temperature on the Surface Discharge of Insulating Paperboard with Different Aging Degree [J]. Gaodianya Jishu/high Voltage Engineering, 2017, 43(8):2724-2732.