Study on Influencing Factors and Model Material Polarization and Conduction Properties of Oil Paper Insulation

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Abstract: With the rapid development of power system, the large transformer reliability and the performance is more and more important, the oil paper insulation electrical characterization of materials are important factors affect the transformer performance and operation reliability. Therefore, it is very important to study the influence factors and model material polarization and conduction properties of oil paper insulation. This paper makes a comprehensive analysis and summary of the relevant research results of domestic and foreign scholars. Through the oil paper insulation system in the conductance properties and the polarization properties of the mechanism and experimental study, oil paper insulation are the influencing factors, for the engineering practice.

1. Introduction

In the power system, the large power transformer couldn't be more expensive and important [1]. The current power transformer commonly uses oil-paper composite insulation, the insulation state and performance will affect the electrical life and mechanical life of the transformer insulation, how to accurately assess the transformer oil-paper insulation state has always been one of major technical problems in industry.

The conductivity characteristics transformer oil and insulating paperboard in high field strength are closely related to their pre-breakdown process under DC voltage, which has theoretical support for analyzing and explaining the pre-breakdown mechanism of oil-paper insulation [2,3]. At present, the research on the influencing factors of the conductivity of insulating paperboard mainly concentrates on the temperature spectrum and spectral characteristics of insulating paperboard. The study of the conductive properties of the transformer oil is not only related to the current injection of the high voltage electrode, but also can estimate the carrier mobility, and furtherly can be related to the dielectric breakdown theory [4].

In this article, the influencing factors of oil-paper insulation have been given out for reference for further engineering practice by studying the experiments and the mechanism of the conductivity and polarization characteristics in the oil-paper insulation system.

2. Study on Oil Paper Insulation Polarization Characteristics

2.1 Method and Principle of Classical Polarization

Based on the principle of dielectric response, the main method of diagnosing the insulation performance of oil-immersed electrical equipment is the medium response method. The method is divided into two parts: frequency domain method and time domain method. The frequency domain method mainly refers to the spectral analysis method (FDS), the time domain method includes polarization depolarization current method (PDC) and recovery voltage method (RVM) [5].

The principle of spectral analysis (FDS) is mainly based on the frequency response characteristics of dielectric polarization [6]. The response (complex capacitance, dielectric loss, power factor, etc.) can not fully reflect the insulation state when applying the single frequency of sinusoidal AC excitation to oil-paper insulation system. In order to get more insulation information, change the frequency of the input excitation and the corresponding response at this frequency could be obtained. All the response is the function of frequency, so the overall insulation state of the insulation system can be analyzed by analyzing the response function.

The recovery voltage analysis method applies a constant DC voltage to the main insulation system of a transformer [7]. As shown in Fig.1a, the duration time was c_t. Due to the role of DC voltage, the polarization phenomenon will occur in insulating medium with bound charge appearing on its surface and the orientation of its internal dipole. The DC voltage applied to the insulation sample is removed and the test piece is short-circuited for a period of d_t ($d_t<c_t$) time. The depolarization process of the insulating medium occurs, and a part of the bound charge due to the polarization is released. As the depolarization time lasts, the depolarization process will continue. The circuit at this time is open, but there is no time to release the bound charge, thus, they will form a voltage at both ends of the test what is called the recovery voltage, also known as the recovery voltage. The curve of the response voltage and the corresponding time is called the recovery voltage curve [8]. This paper focuses on the use of polarization / depolarization current method to study the polarization characteristics of oil paper insulation.

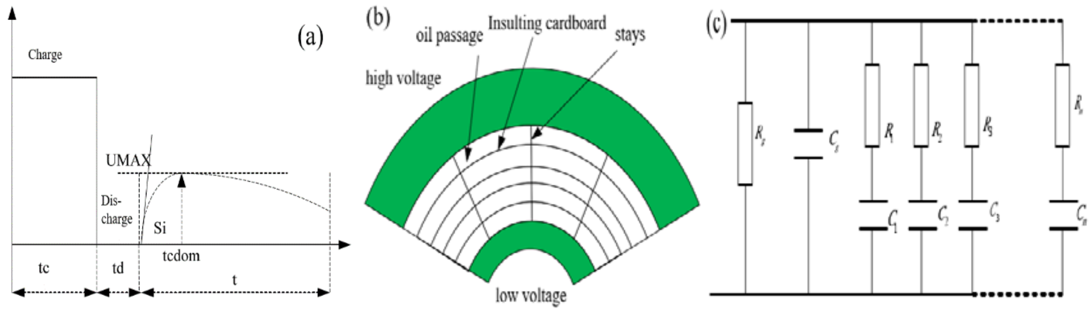


Fig. 1a Recovery voltage curve

Fig. 1b Main insulation system structure

Fig. 1c Oil extended Debye equivalent circuit of insulation system

2.2 Polarization Equivalent Circuit Model

Under the action of the electric field, the transformer insulation system will occur in a variety of polarization. Transformer insulation structure is complex, in addition to insulating paperboard and transformer oil, there are partitions, pads and oil gap, the arrangement is shown in Figure 1b [6].

There is a variety of polarized forms for the insulation structure shown in Fig. 1b. When the transformer internal insulation system is affected by moisture, it will produce a new relaxation polarization process, which will make the relaxation process within the insulation system more complex. Therefore, it is not possible to fully reflect the complex polarization process inside the oil-paper insulation by simply using the Debye model of the RC series branch to equalize the relaxation of the interior of the oil-paper insulation. Jonscher pointed out that in order to fully reflect the relaxation of the combination of dielectric polarization process, it usually could use the sum of a set of exponential functions including n relaxation elements to express, when reflected in the circuit model, that is, with n RC parallel branches to represent. If the conductance, lossless polarization and relaxation polarization are taken into account, the equivalent model of the oil-paper insulation system is shown in Fig. 1c, which is the so-called extended Debye model.

Where R_g is the insulation resistance of the oil-paper insulation system, which mainly reflects the conductivity of the insulation system; C_g represents the sum of the vacuum geometry and the equivalent capacitance of the lossless polarization; the rest of the RC network represents the different types of detrimental relaxation polarization processes, the time constant of each series branch is $\tau_i = R_iC_i$.

2.3 Polarization / Depolarization Current Measurement Method

PDC experimental test principle is shown in Fig. 2a and Fig. 2b, DC power was supplied at both ends of the test sample as the excitation source, switch S_p was closed, switch S_d was off and continued for t_p time. In this process, different kinds of polarization will occur within the test medium under the action of the electric field [6]. At this point, there will be a continuous current flowing through the galvanometer (requires a high accuracy and resolution of the galvanometer), this current is the sum of the conductive current in insulation material the and a variety of polarization current. And then disconnected the switch S_p, closed switch S_d and continued for t_d time. At this time the DC voltage source is removed, the test material was shorted. Due to the previous polarization process, the discharge current in opposite direction will flow through the galvanometer. In general, the longer the polarization depolarization, the more capability in completing the polarization and depolarization process. Also, the polarization depolarization current curve can be depicted by recording the change of the current curve with time.

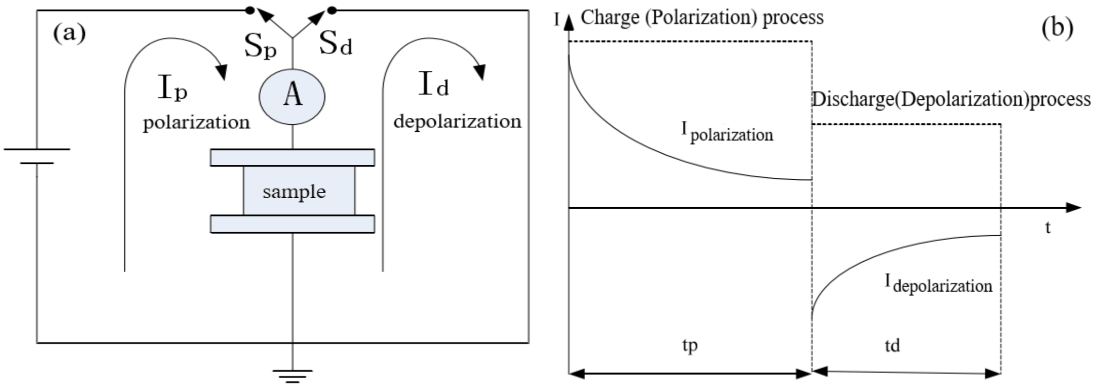


Fig. 2a PDC measurement principle diagram

Fig. 2b Polarization depolarization current pattern

2.4 Analysis of Influencing Factors of Polarization / Depolarization Current

2.4.1 The Effect of Temperature

With the increase of temperature, the kinetic energy of oil molecules in the oil paper insulation increases, the dipole movement is aggravated, the molecule turning is accelerated, the relaxation time is reduced, the relaxation polarization is established quickly, the relaxation polarization is enhanced and the relaxation current density increases [7]. As the DC conductivity of the insulation paper is much smaller than that of insulating oil, the total current density in oil and paper insulation is mainly affected by the insulation paper. Therefore, the effect of temperature on the initial value of the polarization current is small, which has a great influence on the final value.

2.4.2 The Effect of Oil Aging

A total of three transformer oil samples were subjected to a PDC test, which was obtained from the manufacturer's new oil samples, from the middle degree of aging oil samples in a running 110 / 35kV, 20MVA transformer, and a serious degree of aging oil in ae 220 / 110kV, 120MVA transformer which was already out of operation. The relevant parameters of the oil sample are shown in Table 1.

Tab.1 Parameters of oil samples

Characteristics	New Sample	Medium Aging Degree of Sample	Serious Aging Degree of Sample
AC Breakdown Voltage (2.5mm)	42	39	30
Dielectric loss 90°C, 50HZ	0.0025	0.0050	0.0184
Acid value / (mg KOH •g^{-1})	0.018	0.023	0.039
Micro-water content / (mg •L^{-1})	21.4	24.8	32.8
Furfural / (mg •L^{-1})	0.00	0.02	0.25

3. Study on Conductivity of Oil Paper Insulation

3.1 Formation mechanism of conductance of oil paper insulation

The carriers in the liquid dielectric are mainly ion and charged particles. The colloidal particles drift along the electric field direction, forming an electric current, which is called electrophoretic conductance or colloidal particle conductance [8].The conductance of solid dielectrics can be divided into three types according to the type of carriers: Ionic conductivity/Electrolytic conductance; Molecular ionization conductance /Electrophoretic conductance; Electronic conductance.

3.2 Conductivity Measurement System

The most important instrument is the Keithley6517A electrometer, which has a low current amplifier, with measurement range of 1×10^{-17}A~20mA, and the error rate of 1%. The electrometer's built-in ± 1kV DC power facilitates the measurement of insulation dielectric conductance current, and the high voltage copper electrode will be connected through the 237-ALG-2 shielded cable, the typical wiring is shown in Fig. 3a. In the figure, the test sample is placed in a closed polycarbonate container with a height of 200 mm and an inner diameter of 300 mm, and a stable temperature in the range of 20 ~ 150 ° C can be provided by a high temperature oven. I_s the conductivity current flowing through the sample at 2 min.

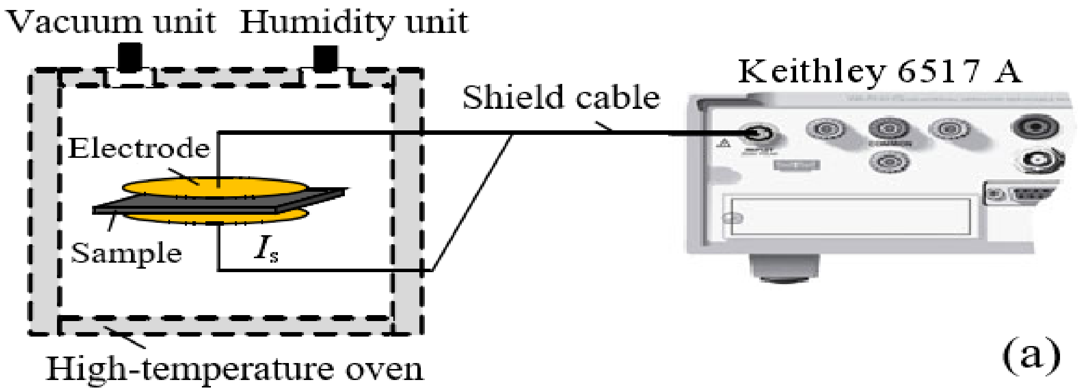
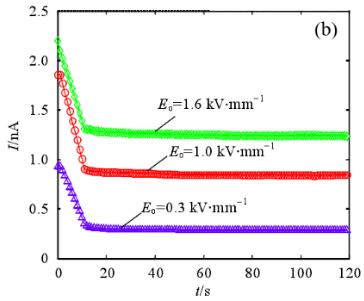
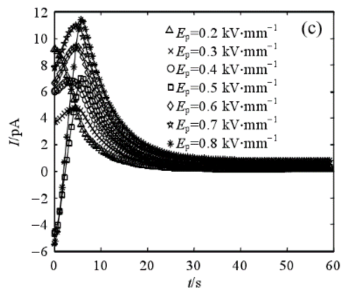


Fig. 3a Typical connections for current measurements

The acquisition of conductance test data is measured and recorded in real time by using LabVIEW software, the sampling rate is 1 time/s, and the data transmission between electrometer and computer is realized by GPIBIEEE-488 bus. Fig. 3b and Fig.3c show the relationship between conduction current and time of the applied voltage under different electric field intensity (Eo and Ep respectively) for both the transformer oil and insulation board.





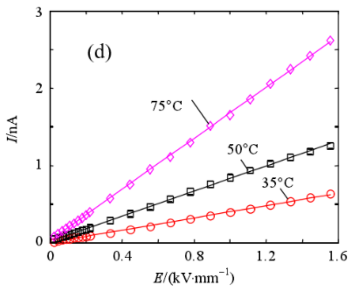


Fig. 3b Temporal variations in conduction current flowing through oil (oil gap: 0.45 mm, temperature: 50 ℃)

Fig. 3c Temporal variations in conduction current flowing through 1 mm insulation paper(temperature: 25℃)

Fig. 3d Effect of temperature on conduction current in transformer oil

3.3 Influencing Factors of Transformer Oil Conductivity

3.3.1 Oil Temperature

Fig.3d shows the effect of temperature on the conductivity of the transformer oil. It is found that the conductivity of the transformer oil increases with the increase of temperature in the range of 35 ~ 70 ℃. This is mainly due to the higher thermal motion of carriers at high temperatures. With the increase of temperature, the viscosity of the transformer oil decreases, the flow rate increases, and the carrier mobility increases.

3.3.2 Fluid Pressure

Fig. 3e is the relation curve between the pressure of the fluid and the conduction current of the transformer oil. With the decrease of the pressure from the atmospheric pressure to the vacuum state, the conduction current of the transformer oil will increase gradually. This is similar to the gas collision ionization, the molecular gap increases with decreasing of the fluid pressure, and then the free travel increases, which means the acceleration time and energy of the carrier will be increased, the number of electrons produced by the collision will also be increased accordingly. This causes the conduction current in transformer oil increasing gradually with the reduction of fluid pressure.

3.3.3 Water Content in Oil

Fig. 3f shows the relationship between the water content in the transformer oil and its conduction current. The results show that the conduction current of the transformer oil increases with the increase of water content in the oil. There are two states of moisture in the damped transformer oil: dissolved state and suspended state. The former has little influence on the conductance of oil, but the latter has great influence. When the oil reaches a saturated state, the water content in the oil is further increased, resulting in the conversion of the dissolved water to the suspended state, and the number of impurities and carriers in the oil is significantly increased. Therefore, the more water is in the oil, the greater the conduction current will be.

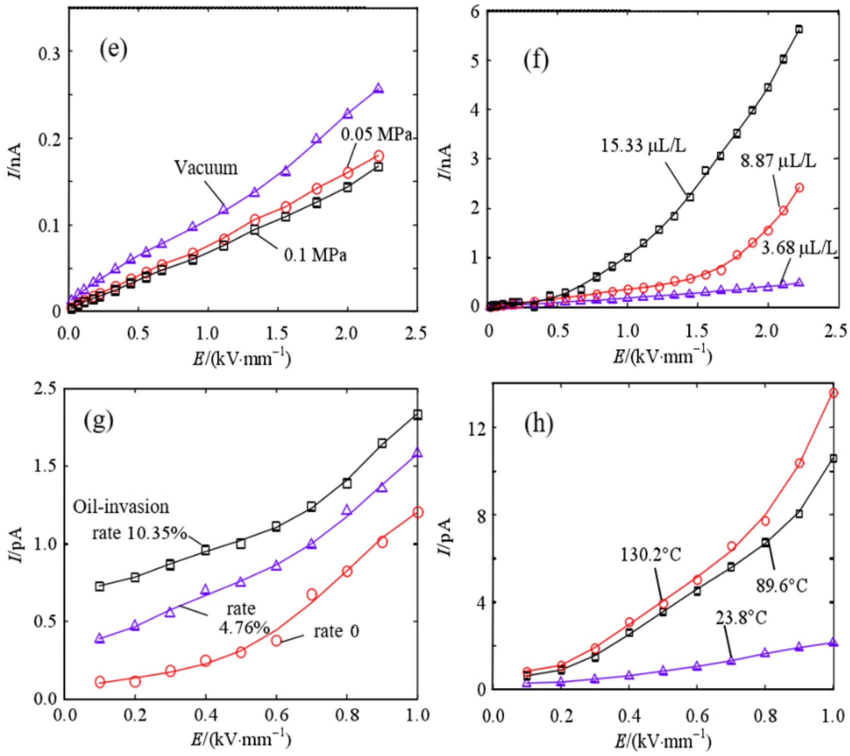


Fig. 3e Variation in conduction current with hydrostatic pressure
Fig. 3f Relation between conduction current and water content in oil
Fig. 3g Conduction current versus oil-immersed level of insulation paper
Fig. 3h Effect of temperature on conduction current in insulation paper

3.4 Influencing Factors of Conductivity of Insulating Cardboard

3.4.1 Oil immersion

Fig.3g shows measurements for the conductance of the insulting cardboard with different levels of oil immersion by applying three electrode model. With the improvement of oil level, the conduction current increased gradually. At low temperature, the conduction of solid dielectrics is mainly caused by impurity ions, which are activated by thermal excitation and undergo directional thermal transitions. However, the conduction performance of the transformer oil is much better than that of insulating board, the carrier motion is stronger, so with further improvement of the oil immersion level, the conduction current increased gradually.

3.4.2 Temperature

Fig. 3h shows the influence of temperature on the electrical conductivity of the insulation board, with the increase of the ambient temperature, the conductivity of the insulation board also improves. From the view of energy band theory, the injection of electrons from the electrode to the medium is the main source of the carrier besides the conduction medium itself.

4. Conclusion

In summary, this paper analyzes the principle and the design of the PDC test by focusing on the influencing factors of the polarization / depolarization current and the conductivity of the insulating board. The conduction current increases obviously when the ambient temperature and the water content lifts or when the liquid pressure declines. Besides, the raise of oil immersion or the power frequency also leads to an improved insulation conductivity.

However, this paper only qualitatively analyses the influencing factors of the polarization / depolarization current, the quantitative analysis of various test results needs further research.

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