The Method for Aging Condition Prediction of Transformer Oil-immersed Cellulose Insulation Based upon the Aging Kinetic Equation

Guang-wei REN*, Jie CHENG, Qing ZHOU, Chu-yang LI and Wen-liang WU
College of Electrical Engineering, Guangxi University, Nanning, China
*Corresponding author

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Abstract. The service life of the transformer is determined by its solid insulation performance. However, it is a rather difficult job to quantitatively evaluate the aging conditions of cellulose insulation materials of the transformer by traditional methods. The existing researches show that the cellulose aging kinetics model of cellulose can establish the functional relationship between the degree of polymerization (DP) and moisture content, aging temperature and aging duration. Therefore, based on the simultaneous considering Arrhenius equation and Ekenstam equation, the purpose of this work is to report an approach that can quantitatively evaluate the aging condition of cellulose insulation of transformer. Furthermore, the present finding of this paper can provide a novel idea for evaluating the aging state of transformer solid insulation.

Introduction

Cellulose insulation materials have been widely used in oil-immersed insulation systems, such as power transformers, high voltage bushings and cable lines. Transformer oil-immersed cellulose insulation system is often subjected to various thermal, electrical, mechanical, chemical and other stresses during operation, which not only gradually degrades its insulation state, but also leads to the deterioration of transformer insulation [1]. During the operation of the transformer, the performance of liquid insulating oil can be improved by oil filtering and oil changing operations, while the solid insulation materials dominate the service life of the transformer main insulation system due to its irreversible and non-replaceable characteristics [2]. Therefore, the evaluation of the aging degree of cellulose materials has received widespread attention and research from scholars in the industry. In recent decades, the evaluation method of the aging state of cellulose insulation has been developed into two types, which is based upon the electrical characteristic parameters [3] and chemical characteristic parameters [4]. In traditional methods utilized the electrical characteristic parameters, scholars have preliminarily realized the qualitative analysis of aging state by testing dielectric loss, time/frequency domain dielectric response spectrum and other parameters. In contrast, in traditional chemical methods, scholars have also preliminarily realized the qualitative (quantitative) analysis of cellulose insulation materials by analyzing the chemical characteristics such as tensile strength, DP value, dissolved furan in oil, alcohol compounds and acid value. The above work provides a lot of theoretical basis and technical support for cellulose insulation evaluation research, but it cannot be popularized in this field due to various limitations. Specifically, the traditional chemical method cannot accurately establish the quantitative relationship between the aging degree and the characteristic parameters due to the difficulty of sampling and the influence of oil change and oil filtering. However, the traditional electrical method is not reliable because it cannot distinguish the influence of aging and moisture on the dielectric response curve from the spectrum curve. Therefore, how to accurately realize the quantitative evaluation of transformer cellulose insulation materials has become an urgent problem to be solved.

The research points out that the aging degradation of cellulose insulation material leads to the destruction of its cellulose microstructure and significant decrease of its mechanical performances, which is directly reflected in the decrease of DP value. Therefore, the DP value has become the key criterion to judge the aging degree of cellulose materials. A large number of the literature show that the decrease of the DP is related to the degree of breakage of cellulose molecular glycosidic bond [5]. By analyzing the functional relationship between the rate of cellulose glycosidic bond breakage and the decrease of DP, an aging kinetic model describing the aging degradation reaction process of cellulose can be established. Therefore, this paper aims to propose a method that can quantitatively evaluate the aging state of transformer cellulose insulation by properly deducing the existing aging kinetic model. In the current work, the laboratory frequency domain dielectric response test platform was set up and oil-immersed insulated pressboard discs with different insulation states are prepared. Afterwards, through the simultaneous analysis of Ekenstam equation and Arrhenius equation, a kinetic equation that can quantitatively estimate the DP value was obtained. Finally, the test results of state evaluation provide a basis for the feasibility verification of the reported method.

Test Platform

In order to obtain the oil-immersed cellulosic pressboard with different insulation conditions, a series of experiments were launched under the controlled laboratory conditions. In this section, pressboard discs (thickness: 2mm, diameter: 160 mm) and transformer oil are utilized. The oil-paper mass ratio is set to 20:1. The transformer oil is the Karamay No.25 naphthenic mineral oil and satisfies the standard of ASTM D3487-2000 (II). The insulating pressboard utilized for condition prediction T4 transformer pressboard, and the parameters of the pressboards and oil are described in Table 1.

Table 1. Parameters of the materials used in the experiment

Cellulosic pressboard		Insulating oil	
Brand	T4 Transformer pressboard	Brand	Karamay No.25 naphthenic mineral oil
Manufacturer	Taizhou Weidmann High Voltage Insulation Co. Ltd. (China)	Manufacturer	Chongqing Chuanrun Petroleum Chemical Co. td. (China)
TS	MD: 144.14 MPa, CMD: 105.76 MPa	Pour point	≤-45℃
Density	1.19g/ cm^3	Flash point	135℃

The pretreatment experiment scheme of oil-immersed cellulosic pressboard is shown in Figure 1. It can be seen that the pretreatment experiment (including vacuum drying and vacuum impregnation of the transformer oil and cellulosic pressboard discs) was firstly completed in the laboratory condition (maintaining 105℃, 50Pa). There are three kinds of cellulosic pressboard discs with different aging conditions were obtained by accelerating thermal aging activities under controlled laboratory conditions (maintaining 150℃, 50Pa).

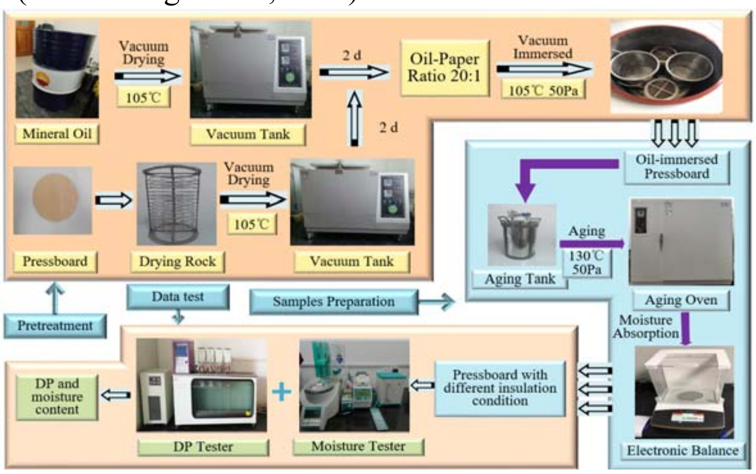

Figure 1. Test flow chart

Model Deduction

Cellulose is a natural linear polymer formed by linking β-D-glucopyranosyl groups by means of 1-4 glycosidic bonds. Where, the number of glucose monomers contained in one cellulose chain is defined as the degree of polymerization. As the transformer insulation system continues to suffer from pyrolysis, hydrolysis, and oxidation reaction during the operation, the 1-4 glycosidic bonds will break, resulting in a decrease in the number of glucose monomers attached to a single cellulose molecule. If DP_0 is defined as the initial DP of cellulose material, and DP_0=1200, and DP_t is defined as the DP after aging reaction time t, CSN is defined as the average number of chain breaks per cellulose chain during the aging process, which is shown in equation (1).

$$CSN = \frac{DP_0}{DP_t} - 1 \tag{1}$$

If it is approximately believed that each chain scission occurs at the end of the cellulose chain, *n* glucose monomers produced by chain scission will be produced after a single cellulose chain scission CSN times. SFCU is defined as the ratio of breakage of glucose monomer to the total number of glucose monomers in a cellulose chain, then SFCU can be represented by equation (2).

$$SFCU = \frac{CSN}{DP_0} = \frac{1}{DP_t} - \frac{1}{DP_0} \tag{2}$$

Assuming that the probability of breakage of glycosidic bonds in per cellulose chain is consistent, SFCU is proportional to the degradation rate of cellulose and the degradation time. This functional relationship can be expressed by the Ekenstam equation (3).

$$SFCU = \frac{1}{DP_t} - \frac{1}{DP_0} = k \cdot t \tag{3}$$

In equation (3), *k* represents the comprehensive rate of cellulose material aging reaction. *T* is the aging reaction time. However, due to the change of the chemical reaction process, the reaction rate *k* is not a constant, so it cannot be obtained through a simple measurement or fitting process. Considering that chemical reaction rate is affected by reaction temperature and reactant concentration, Arrhenius equation is introduced to establish the functional relationship between cellulose aging reaction rate, reaction temperature and reaction time, which is shown in equation (4).

$$k = A \cdot e^{-\frac{E_a}{R \cdot T}} \tag{4}$$

In equation (4), *A* is the pre-exponential factor. *R* is a gas constant, and *R*=8.314J/(mol•K). E_a is the activation energy and E_a≈113 kJ/mol. *T* is the reaction temperature. It is worth mentioning here that due to the particularity of the operating environment of the cellulose insulation system of the transformer (low oxygen, medium temperature), the mechanism that affects the aging degradation is the hydrolysis reaction. Therefore, the pre-exponential factor *A* is related to the moisture content in the insulation system, and the literature [6] gives the relationship between the moisture content and the *A* in a low-oxygen environment, which is shown in equation (5).

$$A = (1.78 \times 10^5 \times mc\% + 1100 \times mc\% + 5.28) \times 10^7 \tag{5}$$

Where *mc%* is the initial moisture content inside the insulating material. By replacing *K* in equation (3) with equation (4), we obtain the kinetic model of SFCU related to aging reaction time, initial moisture content and aging temperature, which is shown in equation (6).

$$\frac{1}{DP_t}-\frac{1}{DP_0}=A\cdot t\cdot e^{-\frac{E_a}{R\cdot T}} \tag{6}$$

To sum up, through the proper derivation of equation (6), an equation that can be used to quantitatively evaluate the aging state of transformer solid insulation is proposed, as shown in equation (7).

$$DP=(\frac{1}{DP_0}+24A\cdot t\cdot e^{-\frac{E_a}{R\cdot T}})^{-1} \tag{7}$$

Evaluation Test

Detailed parameters of oil-immersed pressboard with different insulation state prepared by the experimental process of Figure 1 are shown in table 2. Where, the pre-exponential factor *A* is calculated by equation (5), and the initial *mc%* is the moisture content of the pressboard before the accelerated thermal aging test.

Table 2. The detailed parameters of various insulation pressboards

Sample label	Aging Duration	Temperature	Initial *mc%*	Factor A	Measured DP
1	1d	423.15K	4.8%	4.68×10^9	567.10
2	2d	423.15K	4.8%	4.68×10^9	337.73
3	3d	423.15K	4.8%	4.68×10^9	287.68
4	4d	423.15K	4.8%	4.68×10^9	213.47
5	1d	423.15K	4.6%	4.43×10^9	539.91
6	2d	423.15K	4.6%	4.43×10^9	411.94
7	3d	423.15K	4.6%	4.43×10^9	300.47
8	4d	423.15K	4.6%	4.43×10^9	276.35

By substituting the aging time, initial *mc%*, pre-exponential factor and activation energy in table 2 into equation (7), the predicted DP value can be calculated. the actual measured DP value and predicted DP value are shown in table 3.

Table 3. The detailed parameters of various insulation pressboards

Sample label	Measured *DP*	Predicted *DP*	Error	Sample label	Measured *DP*	Predicted *DP*	Error
1	567.10	477.20	90	5	539.91	493.13	47
2	337.73	297.81	40	6	411.94	310.33	101
3	287.68	216.45	71	7	300.47	226.40	74
4	213.47	170.00	43	8	276.35	178.21	98

As can be seen from table 3, the deviation between the predicted DP value calculated by equation (7) and the measured value is kept within an acceptable range, and the above deviation will not seriously affect the judgment of the aging degree of the pressboard. Therefore, the above experimental results preliminarily verify the feasibility of the reported method for aging state evaluating of the transformer solid insulating materials based upon the cellulose aging kinetic equation.

Conclusions

In this paper, a kinetics model that can quantitatively evaluate the aging degree of transformer solid insulation is derived by combining Ekenstam equation and Arrhenius equation. The following conclusions have been drawn from the existing research findings.

I. By using the Arrhenius equation, the functional relationship between the moisture content, accelerated thermal aging temperature and reaction rate of cellulose aging reaction can be

established.
II. An equation that can quantitatively evaluate the aging degree of transformer solid insulation can be obtained by combining Ekenstam equation with the Arrhenius equation.
III. The error between the DP value calculated by the method and the measured value is kept within an acceptable range. Therefore, the evaluation results preliminarily verify the feasibility and accuracy of the aging dynamics model proposed in this paper.

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