Article

A Study of Electrical Aging of the Turn-to-Turn Oil-Paper Insulation in Transformers with a Step-Stress Method

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Abstract: This study investigates the electrical aging characteristics of oil-paper composite insulation. In this paper, a coils model and test system for oil-paper transformer insulation are designed. The electrical aging tests of the model coils at room temperature and operating temperature are performed using the step-stress method. A new method for estimating the unknown parameters in the inverse power exponent model is proposed, and the inverse power model life formula expressed by voltage and electric field strength is obtained. Considering the electrical aging process at the operating temperature, the allowable field strength of the inter-turn insulation of oil-immersed transformers can be improved. The new parameter estimation method proposed in this paper can be used to calculate the unknown parameters of the step-stress solid insulation aging model. This method has a clear physical meaning and can be solved easily. When the stressed voltage is below a certain threshold value, the life of the transformer coil turn-to-turn insulation grease oiled paper model is longer at operating temperatures compared with that at room temperature; when the voltage is higher than the threshold, it presents the opposite tendency.

Keywords: step stress; electrical aging; oil-immersed paper turn-to-turn insulation; transformer; parameter estimation

1. Introduction

As the core component of power systems, failure of a power transformer results in direct or indirect economic losses, which directly affect the security of the power grid [1–3]. It has been reported that many transformers in service around the world are close to or beyond the end of their design life expectancy [4], so understanding the aging mechanism of transformer insulation systems is crucial [5]. The insulation properties of the turn-to-turn insulation in oil-immersed transformer insulation systems are very important. The breakdown of turn-to-turn insulation occurs occasionally, and a failed transformer is difficult to repair. The aging of oil-immersed paper insulation is influenced by the electric field, temperature, moisture, oxygen, and other factors [6–9]. Among these factors, the damage caused by electrical aging cannot be ignored [10,11]. Understanding the electrical aging properties of oil-immersed paper insulation under various temperatures, evaluating the insulation properties of a power transformer late in its life, and then adopting a flexible life cycle greatly improves the economy and reliability of a power grid operation [12,13].

Because the life of a power transformer is very long and the insulation system aging process is very slow under nominal stress, aging tests always adopt accelerated aging methods, and the transformer lifespan under the normal working state is then calculated [14–17]. According to the loading conditions

of stress, accelerated life tests of insulating materials are divided into constant voltage tests, step-stress voltage tests, and sequence voltage tests [18]. The constant voltage method is the most widely used, but the choice of the test voltage is made blindly and valid data cannot be obtained within a short period of time [19]. In recent years, some researchers have tested the electrical aging life of polypropylene and polyimide films, and obtained good results using the step-stress method. However, the estimated parameters of the solid insulation power model are obtained using partial differential equations, which are difficult to solve by the traditional maximum likelihood method [20–24].

Electrical aging of insulating materials caused by partial discharge (PD) has been extensively studied [25,26]. Partial discharges are key events for insulation diagnosis of power transformers, which is an important means of evaluating the insulation status [27]. The correlation between the PD characteristic parameters and the degree of insulation aging has been established [28]. The changing trend of the PD characteristic parameters have been researched during the aging process of the insulating material to characterize insulation aging [29]. PD is a complex physical process, so PD measurement methods have been widely studied [30]. The pulse current method has the advantages of simple operation and high sensitivity, which has been widely recognized by researchers. In this paper, the pulse current method is used to detect the PD of the sample.

In this paper, we design a model and test system for oil-immersed transformer turn-to-turn insulation and use the step-stress method for testing the electrical aging at room temperature (22 °C) and operating temperature (80 °C). A new parameter estimation method is proposed to increase the speed of solving the inverse power equation, which can replace the traditional complicated maximum likelihood method. A constant stress aging test is used to verify the correctness of the parameter estimation method, and the results of the test are analyzed. In addition, to make the results more universal, we calculate the electric field expressed as an inverse power model of the transformer turn-to-turn insulation and explain the difference between using the actual value and the calculated value for the long-term operation field. The results of this paper provide theoretical support for the aging mechanism of oil-immersed power transformers and oil-immersed insulation using multiple factors, as well as the structural design of turn-to-turn insulation.

2. Electric Aging Theory of Oil-Immersed Insulation under Step Stress

The turn-to-turn insulation of oil-immersed transformers is mainly oil-immersed paper. The electrical aging life of solid insulation obeys the power law, namely:

$$L = AU^{-N} \quad (1)$$

where U —applied voltage; L —insulation life; N —a constant, related to the material performance and the electrical aging mechanism; A —a constant, related to the temperature and geometric shape of the test object.

By Equation (1):

$$U^N L = A \quad (2)$$

where A is the metric of insulation life, subject to all aging processes.

Solid insulation failure has a cumulative effect that meets the Nelson model, that is, in the process of electrical insulation aging, the remaining life of the insulation is determined only by the current state of the insulating material, the voltage applied to the insulating material, and the breakdown probability in the current state, but has nothing associated with its historical process. There are different methods to calculate the insulation aging process from the initial state to the present state, but the residual life is the same [31]. As a result, the step-stress method can be used for the accelerated electrical aging test of the coil turn-to-turn insulation. The testing process of the step-stress method is shown in Figure 1.

U_k ($k = 1 \dots m$) is the voltage at k level; ΔU_k ($k = 1 \dots m - 1$) is step length of voltage; T_{rk} ($k = 1 \dots m - 1$) is the rising time for the No. k step voltage; $T_1 = T_2 = \dots = T_k = \dots = T_{m-1}$ is the stress time, T_m is holding time of the final stress; M is the number of the stress index.

Since it is typical that $T_{rk} < T_k$ in the step-stress test, it is thought that the rising process can be ignored. By Equation (2), based on the accumulation of solid insulation electrical aging characteristics and the Nelson model, with different U_k and T_k :

$$\sum_{k=1}^{m-1} U_k^N T_k + U_m^N T_m = \text{constant} \quad (3)$$

If we do not consider the randomness of breakdown, Equation (3) should be equal to Equation (2). For the step-stress test, T_k in Equation (3) can be classified the same as T_0 , so Equation (3) becomes:

$$T_0 \sum_{k=1}^{m-1} U_k^N + U_m^N T_m = A \quad (4)$$

The step-stress aging test is usually performed with many samples under different T_0 , so that we obtain many groups of T_0 , T_m , U_k , and U_m after the test is completed. By means of the appropriate method, the constants N and A are solved; then the power model life-cycle equation is obtained.

Figure 1. The voltage protocol for step-stress tests.

3. Electrical Aging Test for Coil Model

The step-stress method is selected to conduct the accelerated aging test for the oil-immersed paper insulation at room temperature and operating temperature. The sample's breakdown is defined as the end-of-life, and the holding time to breakdown is called the length-of-life. At the same time, the PD inception voltage is also monitored.

3.1. Test Circuit

Figure 2 shows the electrical aging test circuit for the turn-to-turn oil-paper insulation.

Figure 2. The electrical aging test circuit.

In the Figure 2, 1 is the power grid; 2 is the regulated power supply; 3 is the self-coupling transformer; 4 is no partial discharge transformer; 5 is the protective resistor; 6 is the capacitive voltage divider high-voltage arm; 7 is the capacitive voltage divider low-voltage arm; 8 is the sample; 9 is the coupling capacitor; 10 is the testing impedance.

3.2. Coil Model and Test System

A model coil with the same specifications as the 500-kV power transformer winding wire was produced. The parameters are as follows: outer diameter is 350 mm; inner diameter is 274 mm; 10 turns; thickness of turn insulation is 2.35 mm; cross section of conductor is $a \times b = 2 \text{ mm} \times 10 \text{ mm}$; chamfering radius R is 0.8 mm. Using two pieces of paper-covered wound wire, the double matted wound method is shown in Figure 3a, where 1–8 is the same wire and 1'–8' is another wire. In Figure 3b, 9 is the high voltage coil and 10 is the low voltage coil.

Figure 3. The method of coil winding: (a) Method of connecting wire; (b) Winding structure.

The structure of the actual coil model is shown in Figure 4, where strapping tape is used to fix the high voltage coil and the low voltage coil, and wax silk is wound around the coil terminal in order to prevent PD at the outlet end of the sample.

Figure 4. The structure of coil model.

As shown in Figure 5, the test tank in this paper can be evacuated and heated to a constant temperature.

Figure 5. The electrical aging test tank.

In Figure 5, 1 is the high-voltage coil terminal; 2 is the voltage equalizing electrode; 3 is the transformer oil; 4 is the test coil; 5 is the insulation bracket; 6 is the low-voltage coil terminal; 7 is the insulation cylinder; 8 are the heating and temperature measuring devices. The voltage equalizing electrodes are installed at the high-voltage coil terminal and the low-voltage coil terminal, they can avoid the PD activities out of test samples. Switzerland

The test system of electrical aging is built in the shielding room. As shown in Figure 6, 1 is the self-coupling transformer; 2 is the protection resistor; 3 is the capacitive voltage divider; 4 is the coupling capacitor; 5 is the testing impedance. The PD detector is a DDX-7000 (Hipotronics, Basel, Switzerland) with a sampling frequency of 80 MHz and a sensitivity of 0.1 pC. Before the test is formally carried out, the discharge of the test system is less than 3 pC. The measuring system of PD meets the IEC 60270 standard.

Figure 6. The test system of electrical aging: (a) Power frequency test system; (b) Partial discharge (PD) detector.

3.3. The Pretreatment of the Sample

In order to reduce the dispersion of test results, before every test, coil samples were vacuum dried and impregnated. In this paper, the depositing device is a vacuum jar, and the testing device is a micro water meter. The testing standards are the same as the actual transformer insulation's drying standards. The moisture content in the insulating paper is less than 4%. The drying process is as follows: samples are placed in the vacuum drying chamber and heated to 100 °C for 4 h and then stored in a vacuum at less than 100 mPa and maintained for 16 h. The moisture content of the dried samples is tested, and if the moisture content is larger than 4%, the drying process is repeated. In addition, transformer oil also carried on the dewatering, degassing, and filtration treatment; the parameters meet the requirements of the IEC 60296-2003 standard.

3.4. Preliminary Experiments

In order to obtain the reasonable aging voltage, the preliminary experiment was carried out. The rising speed of the voltage source was 1 kV/s, resulting in the sample breakdown voltage and PD inception voltage, as shown in Table 1.

Table 1. The data of the explorative experiment.

PD inception voltage (kV)	12	11.1	9.2	12.6	10.1	10.5	10.7
	11.2	10.5	10.3	9.6	10.5	11.3	11.6
Breakdown voltage (kV)	88.5	92.5	82.1	93.8	90.1	88.7	89.7
	88.6	86.6	81.3	87.8	84.3	92.1	86.9

(1) The average of PD inception voltage and breakdown voltage is:

$$\begin{aligned}\bar{U}_{PDIV} &= \sum_{k=1}^{14} U_{PDIV}(k) = 10.8 \text{ (kV)} \\ \bar{U}_B &= \sum_{k=1}^{14} U_B(k) = 85.93 \text{ (kV)}\end{aligned}\quad (5)$$

- (2) The standard deviation of PD inception voltage and breakdown voltage is:

$$\begin{aligned}\sigma_{PDIV} &= \sqrt{\frac{1}{13} \sum_{k=1}^{14} (\bar{U}_{PDIV} - U_{PDIV}(k))^2} = 0.913 \text{ (kV)} \\ \sigma_B &= \sqrt{\frac{1}{13} \sum_{k=1}^{14} (\bar{U}_B - U_B(k))^2} = 4.171 \text{ (kV)}\end{aligned}\quad (6)$$

- (3) The minimum PD inception voltage and breakdown voltage estimate values are:

$$\begin{aligned}U_{PDIVmin} &= \bar{U}_{PDIV} - 3\sigma_{PDIV} = 8.061 \text{ (kV)} \\ U_{Bmin} &= \bar{U}_B - 3\sigma_B = 73.417 \text{ (kV)}\end{aligned}\quad (7)$$

The breakdown voltage under the step-stress voltage should be lower than that under continuous stress voltage. To make sure that the aging time is long enough and that the PD inception voltage can be observed, the first level of voltage of the step-stress accelerated life testing voltage method and the estimated value are:

$$\begin{aligned}U_1 &= 0.75U_{PDIVmin} = 6.04575 \text{ (kV)} \\ \Delta u &= 0.1(U_{Bmin} - U_{PDIVmin}) = 6.5356 \text{ (kV)}\end{aligned}\quad (8)$$

3.5. Determination of Test Program

We selected normal (room) temperature and operating temperature as the test temperatures for electrical aging tests. According to the results of the preliminary experiments, 360, 720, 1080, 1440, 1800, 2160, 2520, 2880, 3240 and 3600 s are selected as dwell times, respectively. The first level of step-voltage U_1 is 6 kV with a rising speed of 1 kV/s, recording the breakdown voltage, step series, and the holding time of the last level voltage of each sample. In principle, using the method of step-stress for electrical aging tests, the shorter the step voltage is, the longer the aging time needed, but the dispersivity of the test data is smaller and the results are closer to the true aging process. By Equation (8), we can see that when the step length is 6.9 kV, at least ten times of stress levels from $U_{PDIVmin}$ to U_{Bmin} are needed. Compared with constant stress tests, considering that step-stress tests reduce the breakdown strength of samples, we selected $\Delta u_1 = 2$ kV as the first six stress levels and $\Delta u_2 = 6$ kV as the other numbers of stress levels.

4. Data Processing

4.1. Explanation of the New Parameter Estimation Method

In the step-stress test method, a number of different holding times T_{0i} are often chosen. Assuming that the number of holding times is G , then $T_{0i} = (T_{01} \text{ and } T_{02}, \dots, T_{0G})$. In each holding time T_{0i} , H samples are tested. The voltage resistance index N and the constant A are calculated according to the maximum likelihood method. It is very difficult to obtain the precise solution for the unknown constants N and A represented by Equation (4) using the traditional maximum likelihood method. We propose a new method to solve for the constants N and A . The method is to choose an

initial value for N , named N_0 ; then apply Equation (4) to obtain many A values with the number of $G \times H$. For the H samples with holding times T_{01} , T_{0i} , and T_{0G} , we have the following:

$$\left\{ \begin{array}{l} T_{01} \sum_{k=1}^{m_{11}-1} U_k^{N_0} + U_{m_{11}}^{N_0} T_{m_{11}} = A_{11} \\ T_{01} \sum_{k=1}^{m_{12}-1} U_k^{N_0} + U_{m_{12}}^{N_0} T_{m_{12}} = A_{12} \\ \dots\dots\dots \\ T_{01} \sum_{k=1}^{m_{1j}-1} U_k^{N_0} + U_{m_{1j}}^{N_0} T_{m_{1j}} = A_{1j} \\ \dots\dots\dots \\ T_{01} \sum_{k=1}^{m_{1H}-1} U_k^{N_0} + U_{m_{1H}}^{N_0} T_{m_{1H}} = A_{1H} \end{array} \right. \quad (9)$$

$$\left\{ \begin{array}{l} T_{0i} \sum_{k=1}^{m_{i1}-1} U_k^{N_0} + U_{m_{i1}}^{N_0} T_{m_{i1}} = A_{i1} \\ T_{0i} \sum_{k=1}^{m_{i2}-1} U_k^{N_0} + U_{m_{i2}}^{N_0} T_{m_{i2}} = A_{i2} \\ \dots\dots\dots \\ T_{0i} \sum_{k=1}^{m_{ij}-1} U_k^{N_0} + U_{m_{ij}}^{N_0} T_{m_{ij}} = A_{ij} \\ \dots\dots\dots \\ T_{0i} \sum_{k=1}^{m_{iH}-1} U_k^{N_0} + U_{m_{iH}}^{N_0} T_{m_{iH}} = A_{iH} \end{array} \right. \quad (10)$$

$$\left\{ \begin{array}{l} T_{0G} \sum_{k=1}^{m_{G1}-1} U_k^{N_0} + U_{m_{G1}}^{N_0} T_{m_{G1}} = A_{G1} \\ T_{0G} \sum_{k=1}^{m_{G2}-1} U_k^{N_0} + U_{m_{G2}}^{N_0} T_{m_{G2}} = A_{G2} \\ \dots\dots\dots \\ T_{0G} \sum_{k=1}^{m_{Gj}-1} U_k^{N_0} + U_{m_{Gj}}^{N_0} T_{m_{Gj}} = A_{Gj} \\ \dots\dots\dots \\ T_{0G} \sum_{k=1}^{m_{GH}-1} U_k^{N_0} + U_{m_{GH}}^{N_0} T_{m_{GH}} = A_{GH} \end{array} \right. \quad (11)$$

where i and j are integers, $1 \leq i \leq G$, $1 \leq j \leq H$; M_{ij} is the stress level index of U ; m_{ij} is the voltage of the last level; and T_{Mij} is the holding time of the last level.

Based on the basic physical process of solid insulation aging, assuming a value of N , the following two types of factors affect the dispersion of the A value: the first type is traditional factors such as the solid insulation material process deviation, inherent defects, operating error, system error, and climate change; the second type is caused by the error between the assumed value of N and its true value.

If we take the average of A values obtained from different holding times, the key factor influencing the result in the deviation of A is the error between the assumed value of N and its true value. According to the step-stress voltage method and the discussion above, it is supposed that the assumed value of N approaches the true value when the dispersion of the average of A values decreases.

According to the basic knowledge of probability and mathematical statistics, the size of the variance of a set of data can characterize the dispersion. The data processing procedure is shown in Figure 7.

Calculating average value A_{iave} ($1 \leq i \leq G$) of A_{ij} obtained by H samples under each hold time as:

$$A_{iave} = \frac{1}{H} \sum_{j=1}^H A_{ij} \quad (12)$$

the average value A_{Gave} of A_{iave} obtained by samples under G different holding times is:

$$A_{Gave} = \frac{1}{G} \sum_{i=1}^G A_{iave} \quad (13)$$

so that the variance of A_{iave} and A_{Gave} is:

$$F = \sum_{i=1}^G \left(\frac{A_{iave} - A_{Gave}}{A_{Gave}} \right)^2 \quad (14)$$

If the assumed value of N_0 is the true value of N , the dispersion of A will be minimized, which corresponds to the minimum F . Accordingly, it is supposed that the calculated A_{Gave} is the voltage index and the true value of life. Thus, we can use the iteration method to find a minimum F ; the corresponding N and A_{Gave} is the voltage index and the true value of life.

Figure 7. The process of solving for N and A .

4.2. Solve and Verify the Life Equation

We carried out the step-stress electric aging tests for 100 samples; the experimental results are shown in Table 2. Based on the data in Table 2, we obtained the values for the constant A and voltage life index N ; the estimated values at room temperature are 1.39×10^{27} and 13.38, respectively.

The estimated value of the constant A and the voltage life index N at the operating temperature are 2.06×10^{36} and 18.92, respectively. Substituting A and N into Equation (1), we obtain the electrical aging reverse power model life formula of oil-paper insulation at room temperature and operating temperature, respectively:

$$L = 1.39 \times 10^{27} \times U^{-13.38} \quad (15)$$

$$L = 2.06 \times 10^{36} \times U^{-18.92} \quad (16)$$

To verify the correctness of the step-stress accelerated electrical aging life equation, we performed a constant-voltage electrical aging test at normal and operating temperatures. Constant voltages of 40, 45, 50, 55, 60, 65, 70, 75 and 80 kV are selected. We tested six samples for each voltage. As shown in Figure 8, it is seen that the life curve obtained by the step-stress accelerated electrical aging evenly passes through the points of the life data obtained by the constant voltage method, which shows that the step-stress voltage method can be used in oiled paper insulation electrical aging tests and that the calculating life equation is correct.

Figure 8. The illustration of model performance.

Table 2. Electrical aging test data.

Dwell Time (s)	Title of Data	Room Temperature (22 °C)										Operating Temperature (80 °C)									
360	Breakdown voltage (kV)	66	66	66	66	66	66	72	72	72	72	60	60	60	60	60	66	66	66	66	66
	Steps	15	15	15	15	15	15	16	16	16	16	14	14	14	14	14	15	15	15	15	15
	Hold time on last step (s)	190	209	231	297	331	26	19	66	80	99	127	207	209	257	295	41	56	56	72	76
720	Breakdown voltage (kV)	60	60	60	60	66	66	66	66	72	72	54	60	60	60	60	60	60	60	60	66
	Steps	14	14	14	14	15	15	15	15	16	16	13	14	14	14	14	14	14	14	14	15
	Hold time on last step (s)	585	641	642	681	10	93	278	453	85	137	251	39	145	191	236	236	270	312	389	100
1080	Breakdown voltage (kV)	60	60	60	60	60	66	66	66	66	72	54	60	60	60	60	60	60	60	60	66
	Steps	14	14	14	14	14	15	15	15	15	16	13	14	14	14	14	14	14	14	14	15
	Hold time on last step (s)	487	496	519	584	913	97	121	306	398	209	643	20	66	78	147	199	205	210	350	42
1440	Breakdown voltage (kV)	54	54	54	60	60	60	60	66	66	72	54	54	60	60	60	60	60	60	60	66
	Steps	13	13	13	14	14	14	14	15	15	16	13	13	14	14	14	14	14	14	14	15
	Hold time on last step (s)	182	255	1360	230	315	580	1217	145	459	559	172	540	82	148	199	248	253	253	333	6
1800	Breakdown voltage (kV)	54	54	54	60	60	60	66	66	66	66	54	54	54	60	60	60	60	60	60	60
	Steps	13	13	13	14	14	14	15	15	15	15	13	13	13	14	14	14	14	14	14	14
	Hold time on last step (s)	534	943	1465	284	306	573	228	496	499	535	28	1613	1694	57	144	157	159	218	220	308

Table 2. Cont.

Dwell Time (s)	Title of Data	Room Temperature (22 °C)										Operating Temperature (80 °C)									
2160	Breakdown voltage (kV)	54	54	60	60	60	60	66	66	66	72	48	54	54	60	60	60	60	60	60	60
	Steps	13	13	14	14	14	14	15	15	15	16	12	13	13	14	14	14	14	14	14	14
	Hold time on last step (s)	1542	2246	175	443	589	1155	151	347	454	125	1380	444	1776	165	167	206	216	316	332	337
2520	Breakdown voltage (kV)	54	54	54	54	60	60	60	66	66	66	48	54	54	54	60	60	60	60	60	60
	Steps	13	13	13	13	14	14	14	15	15	15	12	13	13	13	14	14	14	14	14	14
	Hold time on last step (s)	12	611	1742	2520	120	245	1075	401	516	1547	2425	109	417	1425	69	92	261	264	271	295
2880	Breakdown voltage (kV)	54	54	54	54	54	60	60	60	66	66	48	54	54	54	60	60	60	60	60	60
	Steps	13	13	13	13	13	14	14	14	15	15	12	13	13	13	14	14	14	14	14	14
	Hold time on last step (s)	545	710	1430	1668	2217	716	1268	2109	436	542	985	1083	1206	2533	118	150	165	247	302	536
3240	Breakdown voltage (kV)	54	54	54	54	54	60	60	60	66	66	48	48	54	54	60	60	60	60	60	60
	Steps	13	13	13	13	13	14	14	14	15	15	12	12	13	13	14	14	14	14	14	14
	Hold time on last step (s)	534	890	943	1465	2120	297	305	583	1200	2783	1692	3214	90	953	82	143	215	267	622	633
3600	Breakdown voltage (kV)	48	48	54	54	54	54	60	60	60	66	42	54	54	54	60	60	60	60	60	60
	Steps	12	12	13	13	13	13	15	15	15	16	11	13	13	13	14	14	14	14	14	14
	Hold time on last step (s)	1058	3506	315	1428	3184	3300	590	710	2336	972	36	727	938	2635	148	178	185	201	218	1068

5. Discussion

5.1. Analysis of Test Results

It is seen from Figure 8 that when the stressed voltage is below a certain threshold value, the life of the transformer coil turn-to-turn insulation grease oiled paper model is longer at operating temperatures (80 °C) compared with that at room temperature (22 °C). When the voltage is higher than the threshold, it presents a contrary tendency. Figure 9 shows the PD average pulse amplitude of samples under room temperature and operating temperature with a holding time of 3600 s.

Figure 9. Trend of pulse average magnitude.

From Figure 9, when the voltage is below a certain voltage value, the PD intensity at operating temperature is lower than that at room temperature. When the voltage is greater than the threshold value, the PD intensity at operating temperature is greater than that at room temperature. Combined with Figure 9 and the basic structure of a coil, when performing the electrical aging test on the oil-paper by the step-stress voltage, it is assumed that the aging process has experienced different periods. In the first period under the lower voltage where no PD occurred, the aging process is mainly caused by the conduction current and displacement current and the aging speed is very low. In the second period, as the voltage increased, defects such as air-gap, impurities, and water in the oil-paper insulation or near the edge of turns began to breakdown, resulting in PD; the aging speed increased, but because the PD intensity was less, the aging speed was lower. In the third period, as the voltage rose further, the internal oil gap in the oil-paper insulation broke down. Due to the discharge located in the insulating paper and because the discharge intensity was larger, the damaging effects on the molecular structure were stronger, and the aging process accelerated. The speed of the general aging process mainly depends on the last period.

The influences of temperature on the electrical aging process of the turn-to-turn insulation model mainly includes the following two aspects: (1) Compared with room temperature, under the operating temperature the viscosity of oil decreases, the liquidity increases, and the transformer oil can immerge into internal defects in the insulating paper. With the operating temperature, the solubility of water, gas, and other impurities in the oil increases, and the defects in the oil decrease. (2) However, under the operating temperature, cellulose molecules in the insulating paper are more likely to be decomposed, which reduces the electrical strength and mechanical strength of insulating paper. When PD occurs in an oil gap in insulation paper, the damage to the insulation paper increases. The oil under operating temperature has better liquidity, when a PD occurs, it is easier to extrude transformer oil out from the cavity in the paper, resulting in a larger discharge pulse amplitude and more damage to the insulating paper. As discussed above, if the voltage is less than the PDIV of the oil gap in the insulation paper, the electric aging process is slower under the operating temperature, so the aging life is longer than that under room temperature; if the voltage is larger than the PDIV of the oil gap in the insulation

paper, there is larger discharge pulse amplitude and more damage under the operating temperature, so the aging speed increases and the aging life is shorter.

5.2. Discussion of Application

Equations (15) and (16) are based on calculation test results of model samples, so there are differences compared with actual transformer coils and the samples studied by other researchers. The life equation cannot be directly used for the actual transformer voltage residual life assessment or to guide the actual transformer design. Furthermore, it cannot be directly compared with the results of other researchers.

In order to use Equations (15) and (16) for assessing actual transformer turn-to-turn insulation residual life and to provide a reference for the actual structure of transformer turn-to-turn insulation, they should convert the voltage life equation to the electric field intensity life equation, considering that the breakdown generally occurs at the position with the largest electrical field. Therefore, we converted the sample's life equation to the maximum electric field intensity expressed equation. The turn-to-turn electric field is a uniform electric field; when the applied voltage is 30 kV, the electric field is as follows:

$$E = \frac{U}{d} = \frac{30}{2.35} = 12.77 \text{ (kV/mm)} \quad (17)$$

To confirm the actual electric field distribution of a coil's turn-to-turn insulation, we simulated the electric field distribution using simulation software. As shown in Figure 10, the electric field is not a uniform electric field; the maximum field strength is 17.355 kV/mm. The electric field uneven coefficient of the coil model is:

$$f = \frac{E_{\max}}{E_{\text{ave}}} = \frac{17.355}{12.77} = 1.359 \quad (18)$$

The relationship of voltage and maximum field strength of the coil model is:

$$U = \frac{E_{\max} \times d}{f} = \frac{2.35 E_{\max}}{1.359} \approx 1.729 E_{\max} \quad (19)$$

Substituting Equations (19) into (16) yields the aging reverse power model of the transformer turn-to-turn insulation grease paper under operating temperature:

$$L = 6.53 \times 10^{31} \times E_{\max}^{-18.92} \quad (20)$$

This equation can be used to evaluate the residual life of actual transformer coil turn-to-turn insulation, to guide the design of actual transformer turn-to-turn insulation, and for comparison with the accomplishments of other researchers.

If only considering the influence of electrical aging and assuming that the actual transformer design life is 30 years, then according to Equation (20) the long-term average working field strength is 9.32 kV/mm. At present, the allowable field intensity of coil turn-to-turn insulation is only 2.5–4 kV/mm in a 500-kV transformer design [32], which is far lower than the calculation results of (20). This is because: (a) Equation (20) is only influenced by the action of the electric field, while the actual transformer operating life is influenced by thermal, mechanical, and other factors. (b) The “service life” of the transformer design and the concept of “electrical aging life” in this paper is different; the electrical aging life refers to the time insulation failure occurred, but the service life does not mean the insulation material has reached this state. (c) In this paper, the drying degree of sample sand and the purity of the transformer oil is better than the for an actual operating transformer; the size of the sample model is less than the actual transformer coil, so the probability of failure is far less than for the actual transformer. (d) An actual transformer is affected by overvoltage, short-circuit electrodynamic force, and local overheating. However, these factors should not make the allowable field strength of turn-to-turn oil-paper insulation drop by as much as 5.32 kV/mm. Thermal aging is

usually considered as the decisive factor in transformer oil-paper insulation; electric aging is far from enough to affect life expectancy but thermal aging is close to the end of insulation life. Therefore, it is considered a modest increase of turn-to-turn oil-paper insulation design field is viable.

Figure 10. Electric field distribution.

6. Conclusions

Some quantitative relationships between turn-to-turn oiled paper insulation and electrical aging were given to provide reference for increasing the allowed electrical field of transformers, evaluating the aging of oil-immersed power transformers in operating conditions, and designing the structure of a transformer's turn-to-turn insulation. This series of studies provides theoretical support for electrothermal combined stress aging and data analysis in the future. The following conclusions can be drawn:

- (1) It is considered that a modest increase of the turn-to-turn oil-paper insulation design field is viable in the design of turn-to-turn insulation for a large power transformer.
- (2) Step-stress aging can be used for the accelerated electrical aging test of transformer turn-to-turn oiled paper insulation. The proposed method can be used to solve the unknown parameters of solid insulation against the power model under step-stress aging, it has a clear physical meaning, and its operation is simple.
- (3) Compared with that at room temperature, when the stressed voltage is below a certain threshold value, the life of the transformer coil turn-to-turn insulation grease paper model is longer at operating temperatures. When the voltage is higher than the threshold, it presents the opposite tendency.

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