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Assessment of Oil-Paper Insulation Aging Using Frequency Domain Spectroscopy and Moisture Equilibrium Curves

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ABSTRACT Moisture content and aging of oil-paper insulation are two important factors that cause deterioration of the insulation performance of power transformers. The water molecules and aging products are polar, which affects the dielectric response characteristics of the insulation system. Currently, the dielectric response testing technology has realized non-destructive evaluation of the moisture content of transformer insulation. However, the changes in the dielectric response caused by aging products are easily concealed by the influence of moisture, which makes the diagnostic technology ineffective for use in the evaluation of the aging of the oil-paper system. In order to avoid drawback, a new method utilizing frequency domain dielectric spectroscopy (FDS) and the water balance characteristics of the oil-paper insulation is proposed in this paper to evaluate the aging state of oil-paper insulation. The aging of oil-paper insulation will affect the water balance between oil and paper. In this paper, the experimental studies have shown that the water distribution coefficient between oil and paper and the degree of polymerization (DP) of the insulating paper shows a significant linear relationship. Accordingly, in this paper, FDS curves were used to evaluate the moisture content in the insulating paper, oil samples were taken to measure the moisture content in oil, and then the ratio of moisture content in oil and paper were calculated as the aging characteristic parameter. The linear relationship between the characteristic parameter and DP was used to evaluate the aging state of oil-paper insulation. The feasibility of the proposed method is preliminarily verified using oil-paper insulation samples at different aging states and with different moisture levels in the laboratory.

INDEX TERMS Aging state, frequency domain spectroscopy, oil-paper insulation, oil-paper moisture balance curve.

I. INTRODUCTION

At present, the parameters used to evaluate the insulation aging state of oil-immersed transformer include the physical and chemical parameters, such as formaldehyde concentration in oil [1], [2], furan concentration in oil [3], the degree of polymerization [4], [5] and tensile strength of cellulose insulating paper [6]. However, these methods are susceptible to the influence of filter oil, difficult to sample [7], [8], or insensitive to the change of insulation state, which affects the feasibility and reliability of the evaluation. Recently some new methods have been put forward for the evaluation of oil-paper aging, such as dissolved gas analysis based on wavelet LS-SVM regression [9], calculating DP with average activation energy [10]. However, these methods can only be applied to the low degree of aging, which will lead to large errors when the pressboards are with severe aging. Based on dielectric response theory, frequency domain dielectric spectroscopy (FDS) has the advantages of nondestructive testing and strong anti-interference ability [11]. It can make up for the shortcomings of traditional chemical and electrical diagnostic methods, and has attracted more and more attention in recent years. FDS is very sensitive to changes in the moisture content of insulation systems [12]–[14]. It has

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been widely used in the in-situ evaluation of insulation damp state of oil-immersed power transformer. A large number of studies have shown that in addition to the moisture content, the polar products produced by molecular chain breakage in oil-paper insulation during aging also affects the shape of FDS curves [15], [16]. This feature can be employed in the in situ non-destructive assessment of the aging state of oil-paper insulation using the dielectric response testing technology.

In the last decade, many studies have attempted to determine the effective characteristic parameters by dielectric spectroscopy to characterize the aging state of insulating paper [17], [18]. The results show that the effects of moisture and polar aging products on the FDS curves of oil-paper insulation are similar [19]–[25]. It is thus difficult to distinguish the effects of the two factors and consequently the accuracy of estimated moisture content and aging state is affected. When investigating the effect of one factor, if the influence of the other factor is not taken into account, the results will be inaccurate. In fact, a large number of studies have shown that the effect of moisture on the dielectric response curve is significantly greater than that of the aging products [1]. When moisture assessment is carried out, only adding appropriate correction factors can reduce the impact of aging products so relatively accurate results can be obtained. Therefore, Omicron added an aging correction factor to its moisture assessment software upgraded by the Dirana instrument to reduce the interference of aging products on its moisture assessment results. However, the change in FDS curves caused by insulation aging was easily concealed by fluctuations in the moisture content. Although some studies have shown that the influence frequency band of aging and moisture content on FDS curve is different [19], [20], most of these differences can be observed only when the moisture content is low. In an experiment, oil-paper insulation samples at an early aging stage (DP = 1200) and a late aging stage (DP = 250) were observed, and they showed almost coincident FDS curves because of the same moisture content [26]. So far, it has been impossible to use the dielectric response testing technology to effectively evaluate the aging state of transformer insulation.

The results showed that water contents in oil and paper shows a certain proportion under equilibrium conditions, which is mainly affected by the equilibrium temperature. A water balance curve can be used to describe the relationship between the water contents in oil and paper at different temperatures. Oommen curves [21] and Fabre–Pichon curves [22], which have also been used as important bases for evaluating the water content in paper based on water content in oil, are well known. However, results of recent works show that the binding capacity of water molecules weaken after aging and chain breaking of the insulating paper, polarity of the insulating oil increases after aging, and the saturated water content increases to a certain extent [23]; therefore, with increase in insulation aging, some water molecules will break away from the fibers and diffuse 00into the insulating oil, resulting in changes in the water distribution ratio between oil and paper. Experimental results obtained earlier [23], [24] showed that the steady moisture content of seriously aged cardboard is lower than that of non-aged cardboard.


(a) (b)

FIGURE 1. Oil-paper insulation and accelerated aging samples (a) Stainless steel metal bracket (b) Stainless steel sealing tank for aging.

Considering that the dielectric response testing technology is sensitive to moisture content in oil-paper insulation, and the proportion of moisture content in oil-paper insulation is affected by the degree of aging, this work proposes using FDS to determine the moisture content in insulating paper and using the Coulomb method to ascertain the moisture content in insulating oil in order to investigate the correlation between the moisture content and aging state of oil-paper insulation. A new feature parameter and its acquisition method are proposed to evaluate the aging state of transformer oil-paper insulation.

II. EFFECT OF AGING ON WATER DISTRIBUTION RATIO IN OIL-PAPER INSULATION

A. SAMPLE PREPARATION AND TEST FLOW

The insulating paper hand-sheets used in this test were ordinary circular cellulose insulated cardboard (thickness is 2 mm) and insulating oil used is Xinjiang Karamay 25# cycloalkyl mineral insulating oil (0.885g/mL).

Accelerated thermal aging experiments were carried out to obtain oil-paper insulation samples with different degrees of aging. Every 2-mm-thick insulated cardboard piece was processed into a circle with a diameter of 160 mm. They were placed on a stainless steel metal frame (as shown in Fig. 1a) and dried for 48 h in a vacuum drying oil immersion tank (105 °C, 1 mbar). The cardboard pieces were removed and quickly immersed in 25# naphthenic mineral insulating oil degassed by drying. They were then kept in vacuum for 48 h (60 °C, 1 mbar). After pretreatment, the micro-water content in the insulating paper and oil was measured by the Karl Fischer–Coulomb method as approx. 0.51% and 15 mg/L, respectively. The treated insulating cardboard and insulating oil were mixed and packed into five metal aging tanks (as shown in Fig. 1b) with an oil-to-paper mass ratio of 20:1, numbered A1–A5. The tanks were sealed, vacuum pumped, and filled with nitrogen. A1 was preserved as an unaged sample. A2–A5 were put into an aging chamber at 130 °C for 10, 25, 50, and 80 days, respectively. After aging, the aging tanks were opened and the cardboard samples were tested to determine the DP. The DP values for samples in A1–A5 were 1098.48, 750.66, 433.79, 256.8, and 196.12, respectively, representing five samples with different degrees of aging. It is generally believed that the DP of unaged insulating paper is about 1200-1500, which is about 1100 after drying and oil immersion treatment. When DP decreases to 500, the overall insulation life of transformer has entered the mid-term, while when DP decreases to 250, the overall insulation life of transformer has reached the late stage.

In order to study the effect of aging on moisture distribution in oil-paper insulation, five cardboard samples were taken from each sealed tank and exposed to a constant temperature and humidity box maintained at 60 °C and 60% relative humidity to absorb moisture. The cardboard samples were put back into the corresponding aging tanks to mix with the insulating oil for 0 h, 0.25 h, 0.5 h, 1 h, 1.5 h, and 2 h, respectively. The tanks were re-sealed and placed in constant-temperature chambers kept at 85 °C, 70 °C, and 55 °C for water balance. The moisture content of the insulating paper and oil was measured by the Karl Fischer–Coulomb method at regular intervals until the moisture content tended to be stable. When the moisture contents of the oil and paper were stable, water balance curves were drawn on a two-dimensional coordinate map by taking the moisture content values of the oil and paper. Herein, the water contents in oil and paper are expressed as C_{Oil}(mg/L) and C_{paper}(%), respectively.

B. ACQUISITION AND ANALYSIS OF WATER BALANCE CURVE

The water balance curves for the oil-paper system at three temperatures are shown in Fig. 2. It can be seen that when the temperature is constant, aging has a significant impact on the water distribution ratio between oil and paper. Taking the water balance curve at 85 °C as an example, when the moisture content in oil is 80 mg/L, the moisture content in the unaged paper is about 2.2% at equilibrium state, while the moisture content in the severely aged insulating paper is only 1.3%. The other two equilibrium temperatures also show similar trends.

The moisture mass fractions of the insulating paper and oil (w_{paper} and w_{oil}, respectively) were calculated according to Equations (1) and (2). Among them, C_{paper} (%) and C_{Oil} (mg/L) represent the moisture content in paper and oil, respectively, while ($m_{paper}(g)$) and ($m_{oil}(g)$) represent the quality of insulating paper and oil, respectively.

$$w_{oil} = \frac{c_{oil} \times m_{oil}}{c_{oil} \times m_{oil} + c_{paper} \times m_{paper}} \times 100\% \quad (1)$$

$$w_{paper} = \frac{c_{paper} \times m_{paper}}{c_{paper} \times m_{paper} + c_{oil} \times m_{oil}} \times 100\% \quad (2)$$

The variation in the moisture mass fraction of the insulating paper and oil with the DP is shown in Fig. 3. It can be seen that with decrease in the DP (i.e., progress in aging), w_{paper} and w_{oil} decreased and increased gradually, respectively. This shows that the binding capacity of water molecules decreases after aging and chain breakage of insulating paper occurs, which results in a significant change in the proportion of

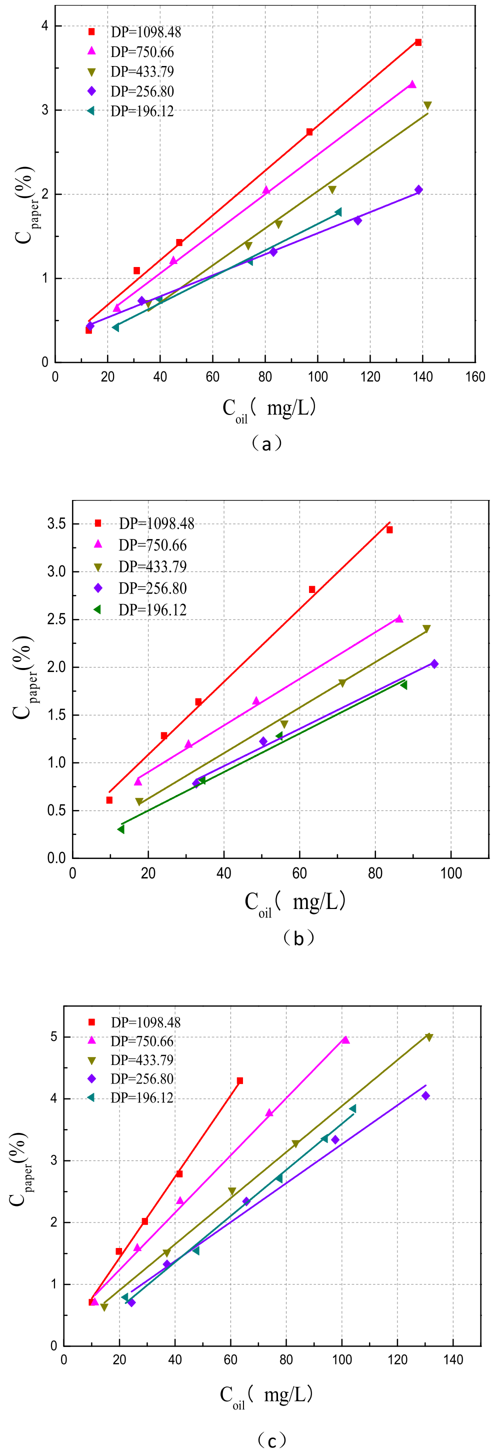

FIGURE 2. Moisture equilibrium of oil-paper insulation at different aging states at different temperatures.

water in the oil and paper. Moreover, temperature change also affects the moisture content. The higher the temperature is, the higher will be the amount of water transferred from paper to oil. Fig. 4 further uses w_{paper}/w_{oil} to represent the water distribution ratio between oil and paper, and draws the variation trend against the DP of the insulating paper.

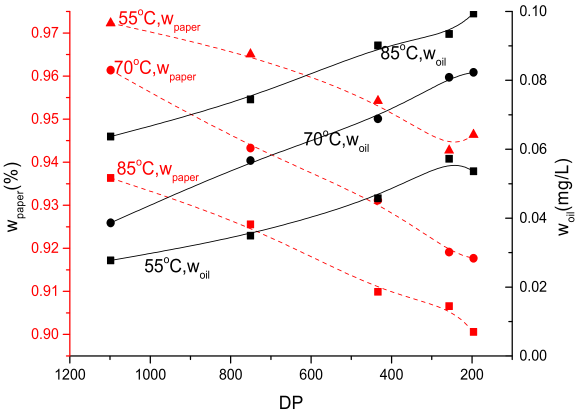

FIGURE 3. Change in moisture content in insulating oil and paper with degree of polymerization.

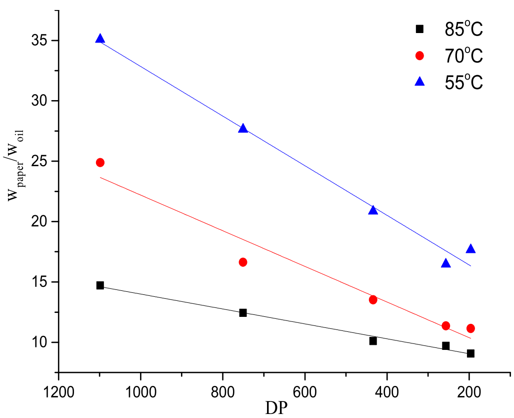

FIGURE 4. Correlation between w_{paper} /w_{oil} and degree of polymerization of insulating paper.

As can be seen in Fig. 4, w_{paper}/w_{oil} decreases significantly with the progress in the degree of aging of the insulating paper. Under the three equilibrium temperatures tested in this experiment (which cover the usual operating temperature range of transformers), the w_{paper}/w_{oil} values of severely aged insulating paper were only about 40–60% of those of the unaged insulating paper. Therefore, changes in the equilibrium proportion of moisture contents of the oil and paper can reflect the degree of aging of the insulating paper to a certain extent.

III. EFFECT OF AGING AND MOISTURE ON FREQUENCY DOMAIN DIELECTRIC SPECTRUM OF OIL PAPER

A. SAMPLE PREPARATION AND DIELECTRIC RESPONSE MEASUREMENT IN FREQUENCY DOMAIN

Oil-paper insulation samples with different moisture contents were prepared by natural moisture absorption of insulating cardboard samples taken from A1–A5. By controlling the moisture absorption time, eight samples with different moisture contents were prepared in the range of 1–5.5% moisture content for each group of samples. A total of 40 samples were obtained from five aging states as shown in Table 1.

TABLE 1. Moisture content of oil-impregnated cardboard samples after moisture absorption.

Sample	Moisture content（%）							
A1	0.98	1.84	2.53	2.76	3.62	3.85	4.51	5.49
A2	1.23	1.42	1.75	2.06	3.15	3.53	4.15	4.93
A3	1.24	1.57	1.71	2.08	2.91	3.37	3.77	4.42
A4	1.26	1.56	1.93	2.51	2.74	3.46	3.87	5.09
A5	1.13	1.27	1.98	2.31	2.76	3.34	4.12	4.75

FIGURE 5. Three electrodes for FDS experiments.

Then, the FDS curves of each sample were obtained by MEGGER IDAX300. The three-electrode structure shown in Fig. 5 was adopted. The sinusoidal excitation signal voltage amplitude was 200 V and the frequency range was 1 mHz–1 kHz [27]. In order to reduce the influence of temperature fluctuation on the FDS curve, a uniform test was carried out at 45 °C.

For the sake of simplicity, Fig. 6 only gives the test results of a few typical samples to analyze the difference in the effect of moisture and aging on FDS curves. Fig. 6 (a) and (b) take A1 and A4 samples as examples, respectively, to show the effect of moisture on frequency domain dielectric spectra. It can be seen that the frequency-domain response curves of dielectric loss increase with increase in the moisture content for both unaged and severely aged samples, and there is a difference of nearly two orders of magnitude between dry samples and severely damped samples. Fig. 6 (c) and (d) show the effect of aging degree on the FDS curve. It can be seen that the effect of aging on dielectric loss spectra is much smaller than that of water. In contrast, for drier samples (Fig. 6 (c)), aging can also increase dielectric loss, while for wetter samples (Fig. 6 (d)), the effect of aging on dielectric loss becomes very weak and difficult to identify.

B. ASSESSMENT OF OIL-PAPER INSULATION STATE BASED ON FDS CHARACTERISTIC QUANTITY

Further extraction of characteristic parameters from FDS curves and evaluation of the state of oil-paper insulation

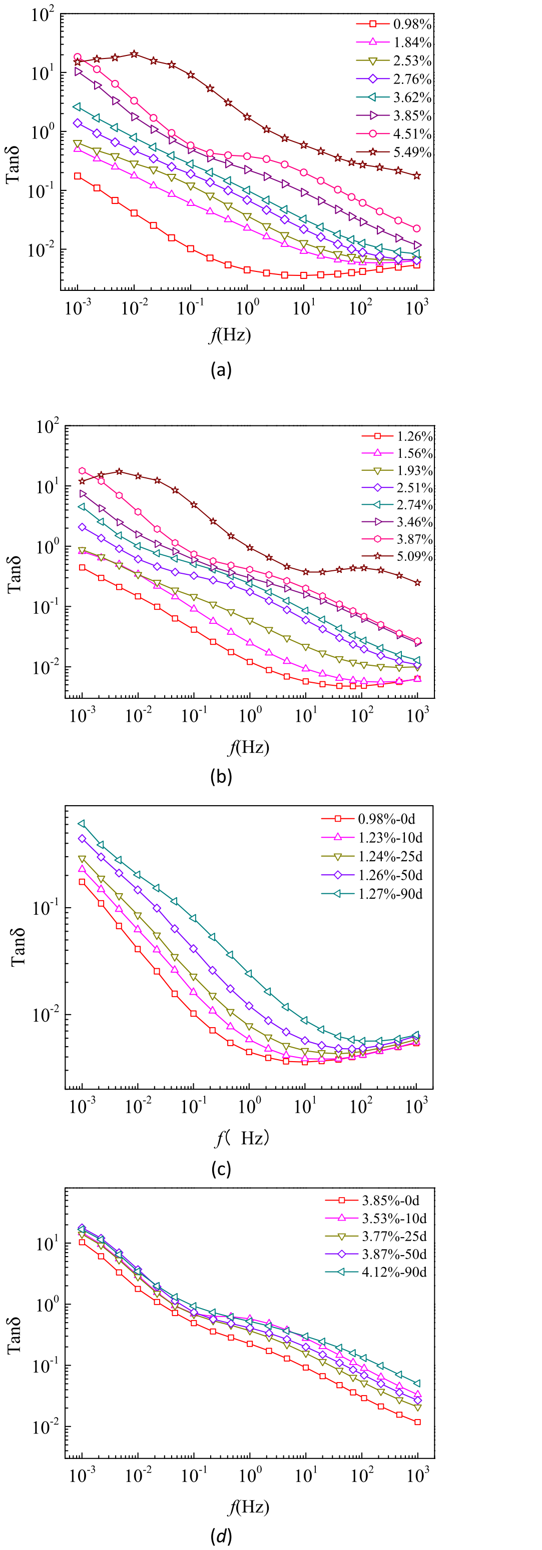

FIGURE 6. tanδ **spectra for (a)(b) cardboard samples at different moisture content and (c)(d) different aging states.**

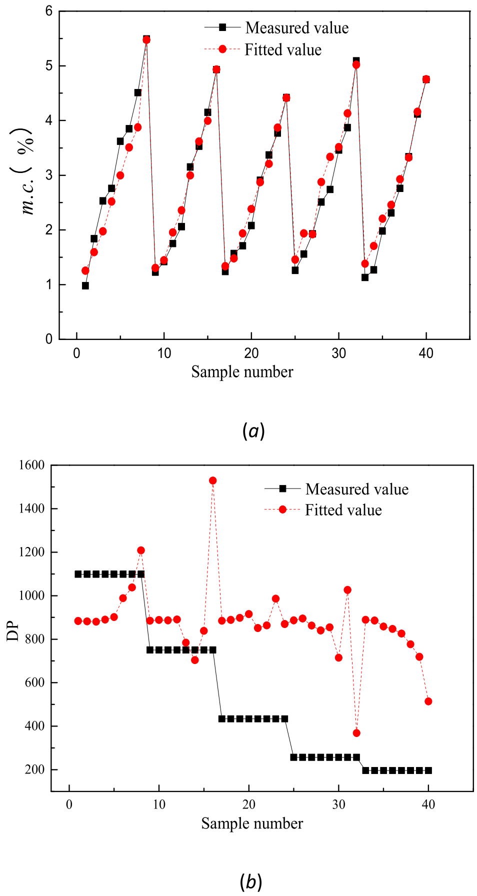

FIGURE 7. Fitting results for (a) moisture content and (b) degree of polymerization obtained by the neural network.

with mathematical algorithm was undertaken. As an example, the dielectric loss corresponding to 20 test frequency points in the range 0.1 mHz–10 kHz on the FDS curve was directly taken as characteristic parameter T, as shown in equation (3):

$$T = [\tan\delta(f_1), \tan\delta(f_2), \cdots, \tan\delta(f_{20})] \quad (3)$$

With the input of FDS characteristic parameter T and the output target of $m_{paper}(\%)$ and DP, the neural network fitting method was used. The number of nodes in the input layer, hidden layer, and output layer was 20, 10, and 1, respectively. A sigmoid function was used as the excitation function of the hidden layer and L-M was used as the training algorithm. Twenty-eight of the 40 samples were taken as training samples, six as calibration samples to measure the generalization ability of the neural network training, and the remaining six as validation samples. The validation samples had no effect on the training process of the neural network, and only evaluated the network performance independently during and after the training process. The network judged the goodness of fit by calculating the mean square error and regression analysis, and the training ended when generalization ability stopped improving.

Fig. 7 shows the fitting results of the moisture content and degree of aggregation of 40 samples. It can be seen that this method can accurately fit and predict the moisture content. The maximum fitting relative error was about 30% and the average was 4%. This shows that even though aging

TABLE 2. Sampling conditions and summary of the tests.

Number	Accelerated Aging Conditions: Temperature (°C)	Accelerated Aging Conditions: Initial moisture of paper (%)	Time (day)	DP	C_{paper}(%)s (Evaluation value)	C_{oil}(mg/L)	w_{paper}/w_{oil}	m_{total}(g)	Remarks
TS1	110	1.12%	10	950	1.31	23	25.63	1.84	---
TS2			50	760	1.12	25	20.16	1.59	
TS3			100	450	0.85	30	12.75	1.24	
TS4		2.95%	10	965	3.12	60	23.40	4.39	
TS5			50	420	2.35	80	13.22	3.41	
TS6			100	198	2.15	88	10.99	3.17	
TS7	90	5.12%	40	962	5.12	110	20.95	7.24	
TS8			90	780	4.63	118	17.66	6.60	
TS9			130	550	3.56	108	14.83	5.13	
TS10			310	400	2.3	113	9.16	3.44	
TS11	120	1.4%	0	1100	1.36	29.08	21.11	1.93	After aging to a certain extent, the cardboard was taken out and exposed to air with R.H. 80% for different times and then put into insulating oil to simulate the insulation moisture content conditions.
TS12			0	1100	1.60	45.92	15.66	2.30	
TS13			0	1100	2.52	73.65	15.38	3.62	
TS14			10	763	1.25	33.04	16.96	1.78	
TS15			10	763	1.89	50.12	17.00	2.71	
TS16			10	763	2.46	71.9	15.40	3.54	
TS17			25	514	1.60	55.48	12.98	2.33	
TS18			25	514	1.84	67.8	12.20	2.69	
TS19			25	514	2.52	95.59	11.86	3.69	
TS20			50	349	0.99	30.1	14.73	1.42	
TS21			50	349	1.40	60.02	10.51	2.07	
TS22			50	349	2.15	92.17	10.51	3.18	
TS23			80	225	1.03	44.16	10.54	1.53	
TS24			80	225	1.87	70.64	11.88	2.73	
TS25			80	225	1.91	85.27	10.08	2.83	

has some influence on the characteristics of FDS, it will not cause obvious errors in the evaluation of the water content. However, the fitting error of DP value was very large. The fundamental reason is that the contribution of aging polar products to the dielectric spectrum of FDS is far less than that of water.

IV. AGING ASSESSMENT METHOD OF OIL-PAPER INSULATION BASED ON FDS AND WATER BALANCE CURVE AND EXPERIMENTAL VERIFICATION

A. A METHOD FOR EVALUATING AGING STATE OF OIL-PAPER INSULATION

According to the analysis results of the third part, it is difficult to accurately evaluate the aging state of insulation only using the characteristics of FDS curves unless additional feature information is added because the fluctuation of moisture can easily conceal the effect of aging products on the FDS curve. The results discussed in the second part of this paper show that aging has a significant effect on the water distribution between oil and paper. The w_{paper}/w_{oil} ratio of the severely aged oil-paper insulation system was only about 40–60% of that of the unaged oil-paper insulation system, and the value was negatively correlated with the degree of polymerization of oil-paper insulation.

Therefore, w_{paper}/w_{oil} is proposed as a characteristic parameter to evaluate the aging state (DP) of oil-paper insulation. For field transformers, w_{oil} can be obtained directly by an oil sampling test or an on-line monitoring sensor, while w_{paper} can extract characteristic parameters employing a FDS dielectric spectrum and calculation. Previously, it has been proven that this method can accurately evaluate the moisture content of oil-paper insulation samples in the laboratory. Of course, considering that the temperature has a great influence on the relationship between w_{paper}/w_{oil} and DP, we should pay attention to the temperature value of the test when evaluating.

B. VALIDATION OF EVALUATION METHODS

In order to verify the feasibility of the above assessment methods, accelerated aging tests were conducted on 25 groups of samples (TS1–TS25) under different conditions. The material used in the test and the pretreatment process was consistent with those described above. The difference was that after the drying pretreatment, the insulating paper samples were not directly impregnated with degassed drying insulating oil, but exposed to air with R.H. 80% for a period of time, thereby obtaining insulating paper samples with different initial moisture contents of 1.12%, 2.95%, and 5.12% before vacuum impregnation and aging. The purpose was to investigate the universality of the proposed method in oil-paper systems with different moisture contents.

Table 2 lists the test and sampling conditions. The sealed tank as regularly removed from the thermostat and kept in a sealed state at 70 °C for 10 days until the moisture was stable

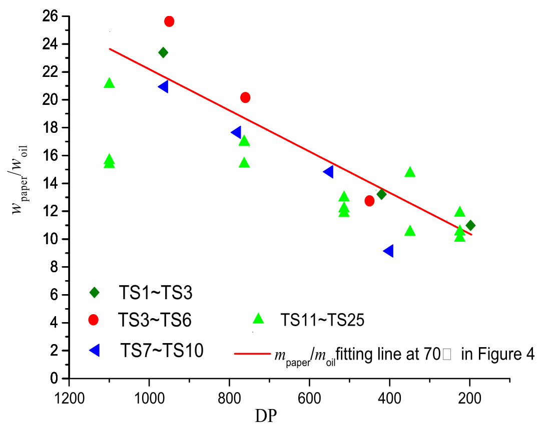

FIGURE 8. w_{paper}/w_{oil} **for TS1-TS2.**

and then opened. The water content in the oil was measured by the Karl Fischer–Coulomb method. Then, the cardboard samples were taken out and put into the three-electrode structure shown in Fig. 2. The FDS characteristic curve of the cardboard was tested at 45 °C for 30 min. The water content was evaluated by the third part of a trained neural network. For samples TS1-TS10, FDS measurements were carried out immediately after the cardboard was removed from the sealed tank and put into three electrodes. Samples TS11-TS25 were exposed to R.H. 80% air for different times after removal, and then put into three electrodes for FDS measurements after a certain amount of moisture was absorbed, thereby simulating the damp state of insulation during aging.

It should be pointed out that 70 °C was used as the water balance temperature because the water balance curves at three temperatures have been obtained in this study, and one of them was chosen as the basis of analysis for convenience. However, 45 °C was chosen as the test temperature for the FDS characteristic curve, because the aforementioned training samples of the neural network for water content fitting were obtained under 45 °C. In order to reduce the error, 45 °C can be used as the test temperature directly. The moisture content test values of insulating oil and the moisture content evaluation values of insulating paper for each sample are shown in Table 2. The ratio of water content to mass fraction in paper and oil w_{paper}/w_{oil} and the absolute value of water content in oil paper ($m_{\text{total}}(g)$) are also given in the table.

It can be seen that the amount of moisture in the insulation system obviously affects its aging rate. At an aging temperature of 110 °C, the aging rate of oil-paper insulation with 1.12% initial moisture content is slower than that with 2.95% moisture content. Because most of the moisture is absorbed by insulating paper, the moisture content of oil does not change significantly during the whole aging stage, while the moisture content of paper decreases significantly with progress in aging, but it mainly depends on the moisture level of the insulating system. In contrast, the characteristic w_{paper}/w_{oil} shows the correlation of aging degrees of insulating paper in various cases. Fig. 8 shows the correlation between w_{paper}/w_{oil} and DP for each sample, and compares the relationship curve for w_{paper}/w_{oil} and DP under 70 °C in Fig. 4. It can be seen that the test points of TS1–TS10 satisfied the linear relationship well, while the dispersion was larger for TS11-TS25, but the linear relationship was essentially satisfied, validating the proposed method.

V. CONCLUSION

(1) The effect of aging on the water distribution ratio between oil and paper was studied quantitatively. The results showed a linear correlation, wherein $\boldsymbol{w_{paper}/w_{oil}}$ decreased with decrease in the polymerization degree of the insulating cardboard. The $\boldsymbol{w_{paper}/w_{oil}}$ value of severely aged insulating cardboard was only about 40–60% of that of unaged paper.

(2) The sensitivity of the FDS characteristic curve to changes in the moisture content in oil-paper insulation was much greater than to the aging of oil-paper insulation. Taking test data of samples with different aging and moisture levels as reference, we could extract features and evaluate the moisture contents of unknown samples accurately by a mathematical analysis algorithm, but we could not evaluate the extent of aging of oil-paper insulation.

(3) It is proposed that the moisture content in paper (C_{paper}) be evaluated by FDS characteristic curves, and the moisture content in oil (C_{oil}) be determines by FDS characteristic curves assistantly . The distribution ratio of moisture in insulating paper and oil ($w_{\text{paper}}/w_{\text{oil}}$) can be used as the characteristic parameter to judge the degree of aging of oil-paper insulation.

In this paper, a new idea for evaluating the aging state of oil-paper insulation is proposed, and satisfactory results obtained in the laboratory are reported. However, there are still many issues that need to be solved in the application of this method to the evaluation of the aging status of transformer insulation systems in situ. For instance, the temperature of the windings presents uneven distribution along the direction of the winding height; on the one hand, the aging state of the insulation paper varies from place to place, and the retention capacity of the insulation paper for water content also presents distribution characteristics.; on the other hand, the winding and oil temperature of transformers vary with the load and environmental temperature. The change shows fluctuating characteristics, and the moisture content keeps a dynamic balance between the oil and the paper. All these factors will bring great difficulties to the application of this method in the field and thus much work needs to be carried out in this regard in future.

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