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A New Method for Evaluating Moisture Content and Aging Degree of Transformer Oil-Paper Insulation Based on Frequency Domain Spectroscopy

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Abstract: The condition of oil-paper insulation is closely related to the life expectancy of a transformer. The accurate results of oil-paper have not been obtained due to the impact of influencing factors. Therefore, in order to improve the evaluation accuracy of oil-paper insulation, in this paper, oil-paper samples which were prepared with different aging and moisture content were analyzed by frequency domain spectroscopy (FDS). Results show that when the moisture content is less than 2%, the range of 10^1~10^3 Hz is mainly affected by moisture and aging has little effect. However, with the increase of moisture content, the effect of aging degree on this band became increasingly prominent. S_m, which represents the integral value from 10^{-1} to 10^{-3} Hz, and S_{DP}, which represents the integral value from 10^1 to 10^3 Hz, were extracted as characteristic parameters of moisture content and aging degree respectively. Compensation factors γ which represents the influence ratio of moisture on S_{DP} and ϕ which represents the influence ratio of aging on S_m were introduced to compensate for the influence of moisture content and aging degree on characteristics respectively. Then, a new method was proposed to evaluate the condition of oil-paper based on compensation factors. Through this method, the influence in characteristics can be eliminated by the obtained actual compensation factors, thus distinguishing the internal influence between moisture content and aging degree on FDS. Finally, this method was verified by field test.

Keywords: aging degree; characteristic parameters; compensation factor; frequency domain spectroscopy; moisture content; oil-paper insulation

1. Introduction

Power transformer is one of the most expensive and important pieces of equipment in power grid [1,2]. The safety and stability of such transformers are both important and necessary in operating power systems [3]. Oil-paper insulation is an important form of power transformer insulation system; the remaining life of the transformer largely depends on the insulation status of oil-paper which is affected by thermal, mechanical, partial discharge and other aging factors in the long-running process [4–6]. Therefore, using an accurate assessment tool to evaluate the condition of oil-paper insulation has become a popular research topic.

Aging degree and moisture content (MC) are two important aspects of oil-paper insulation state assessment. The increase of moisture content will raise dielectric loss and reduce breakdown voltage of oil-paper insulation which will damage the insulation structure and affect normal operation of equipment [7,8]. The aging degree of oil-paper insulation will directly determine the service life of the transformer. When the aging degree reaches a certain extent, with the degradation of insulating paper, the breakdown voltage and mechanical properties of the insulation system will significantly reduce, thus the transformer main insulation will be unable to meet the requirements, and the insulation system will be completely ineffective. Various methods have been developed to help to evaluate the condition of the insulating paper, including the breakdown voltage, the tensile strength, the degree of polymerization and Karl Fischer coulometric titration [9,10]. More recently, Frequency Domain Spectroscopy (FDS) [11–13], Polarization and Depolarization Current (PDC) [14–16] and Recovery Voltage Measurement (RVM) [17], which are based on dielectric response, have become a hotspot for scholars to study because of easy operation and no need for sampling. Compared with PDC and RVM, FDS has the advantages of rich insulation information and strong anti-interference ability, so it has great potential in oil-paper insulation condition evaluation [18].

A lot of valuable research about oil-paper insulation condition assessment and the influence of moisture and aging on FDS measurement have been done. Blennow [19] studied measurement of moisture content in field transformer based on field experience, and presented that precautions should be taken with the results to minimize effects caused by equipment remaining connected to the transformer as well as by external conditions, while the internal relationship between aging and moisture had not be explored. Belén García and Juan Carlos Burgos' studies [20–22] focused on moisture diffusion in oil-paper insulation, and explored the influence of temperature, thickness of cardboard, aging and other factors on moisture diffusion coefficient between oil and paper. The mechanism of factors affecting water diffusion was elaborately demonstrated, which revealed an internal relation between moisture and aging degree of paper. Studies of Jadav et al. [23] and Liao et al. [23,24] explored the influence of aging degree and moisture content of oil-paper insulation on FDS. The results showed that aging mainly affects the low-frequency range of tanδ curves, while moisture has an effect in the whole measurement frequency domain, and the effect of moisture on tanδ curves is more prominent than that of cardboard aging. As above, although a lot research has been done related to condition assessment, FDS or internal relationship between moisture and aging, there still remains challenging problems that the assessment results of aging condition and moisture content are mostly combined rather than separated, which causes the inaccuracy of condition assessment results. Therefore, exploring effective ways to evaluate the condition of oil-paper insulation and separating the influences of aging degree and moisture content on dielectric response measurements are still challenging problems. In this study, different with the previous studies, aging degree and moisture content compensation factors are introduced to eliminate the influences on different frequency bands between aging and moisture. Therefore, problems in previous literature can be solved by compensating one factor when measuring another, and compensation factor algorithm is proposed to achieve accurate assessment on the field test based on compensation factors and characteristic parameters.

In this paper, an accelerated thermal aging experiment was carried out under laboratory condition and five sets of oil-paper insulation samples were prepared with different aging degree and moisture content. Firstly, the effect of moisture content and aging degree of insulation paper on FDS curves were studied, and characteristic parameters were put forward to represent aging degree and moisture content. Then, by analyzing the combined effects of moisture and aging on FDS, this paper introduced the moisture compensation factor (MCF) and aging compensation factor (ACF), and proposed a new method that could eliminate the mutual influences between moisture content and aging degree to evaluate the condition of oil-paper insulation.

2. FDS Test Principle and Test Device

2.1. Theoretical Basis

Under sinusoidal AC electric field, displacement polarization and relaxation polarization are generated in the dielectric, which brings electric conduction loss and polarization loss. Thus, the dielectric can be equivalent to complex capacitance [25]. When AC voltage $U(\omega)$ with an angular frequency of $2\pi f$ is applied to both ends of the dielectric, the through-current of the dielectric is:

$$I(\omega) = j\omega[C'(\omega) - jC''(\omega)]U(\omega) \tag{1}$$

In Equation (1), $C'(\omega)$ and $C''(\omega)$ is the real part and imaginary part of complex capacitance respectively, by performing Fourier transform on Equation (1), there is:

$$I(\omega) = j\omega C_0[\varepsilon_\infty + \chi'(\omega) - j(\frac{\sigma_0}{\varepsilon_0 \omega} + \chi''(\omega))]U(\omega) \ = j\omega C_0(\varepsilon'(\omega) - j\varepsilon''(\omega)) \quad (2)$$

In Equation (2), C_0 is geometric capacitance; $\chi'(\omega)$ and $\chi''(\omega)$ are real and imaginary part of the complex polarization respectively; ε_0 is the vacuum dielectric constant (ε_0 = 8.854 × 10^{-12} F/m); ε_∞ is optical frequency dielectric constant; σ_0 is the DC conductivity of material; $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ are real and imaginary part of complex permittivity. The frequency domain dielectric loss is defined as:

$$\tan\delta(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} = \frac{C''(\omega)}{C'(\omega)} = \frac{\frac{\sigma_0}{\varepsilon_0 \omega} + \chi''(\omega)}{\varepsilon_\infty + \chi'(\omega)} \quad (3)$$

In Equation (3), $\sigma_0/\varepsilon_0\omega$ presents the loss of free charge movement in the material, $\chi''(\omega)$ is the loss caused by the charge transfer polarization.

2.2. FDS Test Device

FDS test device is a three-electrode test system which was made in laboratory, the schematic diagram is shown in Figure 1. When measuring, samples were placed between the measuring electrodes and pressed with the spring. Before each measurement, the entire electrode was placed in insulating oil which is dried and degassed. Then, in order to prevent the difference between internal and external temperature during each FDS measurement, the whole three-electrode device was put into the 30 °C constant temperature box for 6 h. Analyzer of measuring FDS is IDAX300, test frequency range is 10^{-3}~10^{3} Hz, output voltage peak is 200 V.

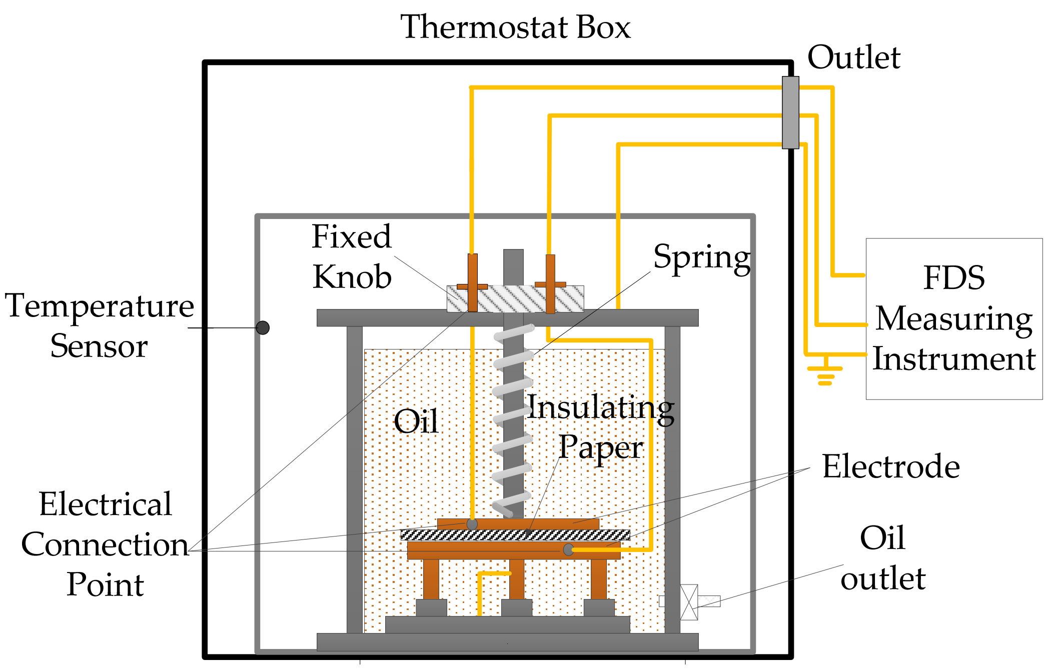


Figure 1. The principle diagram of FDS test device.

2.3. Preparation of Oil-Paper Insulation Samples

In this paper, 1 mm thick cardboard and 25# naphthenic mineral insulating oil were selected as experimental material. Five sets of oil-paper samples were prepared with different aging degree and moisture content under laboratory conditions. In order to control the initial state of the samples, the pretreatment steps are as follows: firstly, insulation papers were dried at 90 °C/50 Pa vacuum box for 48 h, and insulating oil which had been degassed was heated up to 50 °C; then, the transformer oil and insulation pressboard were impregnated for two days in 40 °C/50 Pa vacuum box.

The pretreated insulating oil and paper which were set to 20:1 ratio and were placed into the iodine bottle with some copper. The ratio of oil-paper (20:1) was utilized to simulate the ratio in the actual transformer. The bottle in the open state was put into the test chamber with temperature control accuracy of ±0.5 °C; the aging temperature was set to 120 °C. Several sets of oil-paper insulation samples aged 0 days, 14 days, 35 days, 55 days and 80 days were obtained. Samples with different aging degree were placed in a vacuum drying oven (110 °C/50 Pa) for 24 h, so as to obtain dry samples. The average moisture content of dried samples measured by MS-C Karl Fischer was 0.21%. It is worth noting that this content is lower than that of the actual new transformer [26], so the samples can be considered as dried samples. Then, the DP (degree of polymerization) of different aging time samples were tested; the measured results were shown in Table 1.

Table 1. Average DP of different aging days.

Aging Days	0	14	35	55	80
Average DP	1250	932	740	504	402

The moisture content of oil-paper insulation samples in the experiment were controlled at 0% to 4%. Dried oil-paper insulation samples were placed in a wet box with natural moisture absorption; moisture content was dominated by the variation of sample's weight. Finally, at each aging time, oil-paper insulation samples were prepared with moisture contents of 0.21%, 0.98%, 1.98%, 2.97%, 3.90%. The sets of obtained samples are shown in Table 2; sample groups are represented by A_0, B_0, C_0, etc.

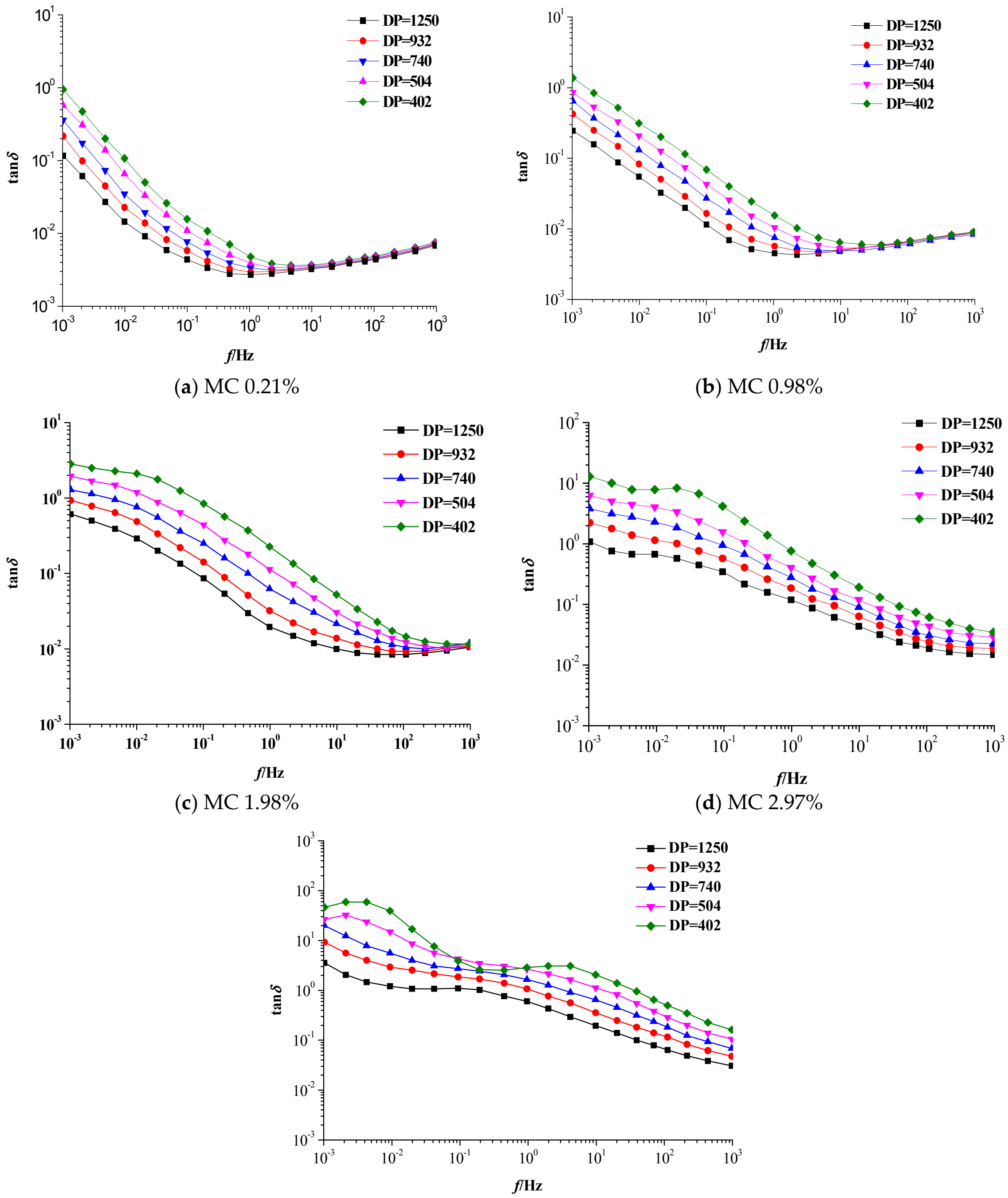
Table 2. Sample sets with different aging days and moisture content.

DP \ MC/%	**0.21**	**0.98**	**1.98**	**2.97**	**3.90**
1250	A_0	A_1	A_2	A_3	A_4
932	B_0	B_1	B_2	B_3	B_4
740	C_0	C_1	C_2	C_3	C_4
504	D_0	D_1	D_2	D_3	D_4
402	E_0	E_1	E_2	E_3	E_4

3. Experimental Results and Analysis

3.1. The Influences of Aging and Moisture on tanδ Curve

Figure 2a–e shows the effect of aging on curves varied with moisture content. When moisture content is low, aging degree mainly affects the FDS at a low-frequency range (10^{-1}~10^{-3} Hz) and moisture affects all frequency range; this is consistent with the experimental results of the literature [27]. The main reason is that in the low-frequency range, interface polarization of oil-paper insulation plays a leading role, but with frequency enhancing, the rate of polarization cannot keep up with the rate of the alternating electric field. However, when the frequency is higher than 10^{-1} Hz, steering polarization plays a leading role. (In this paper, low-frequency range represents 10^{-3}~10^{-1} Hz, high-frequency range represents 10^{1}~10^{3} Hz).



(**a**) MC 0.21% (**b**) MC 0.98%

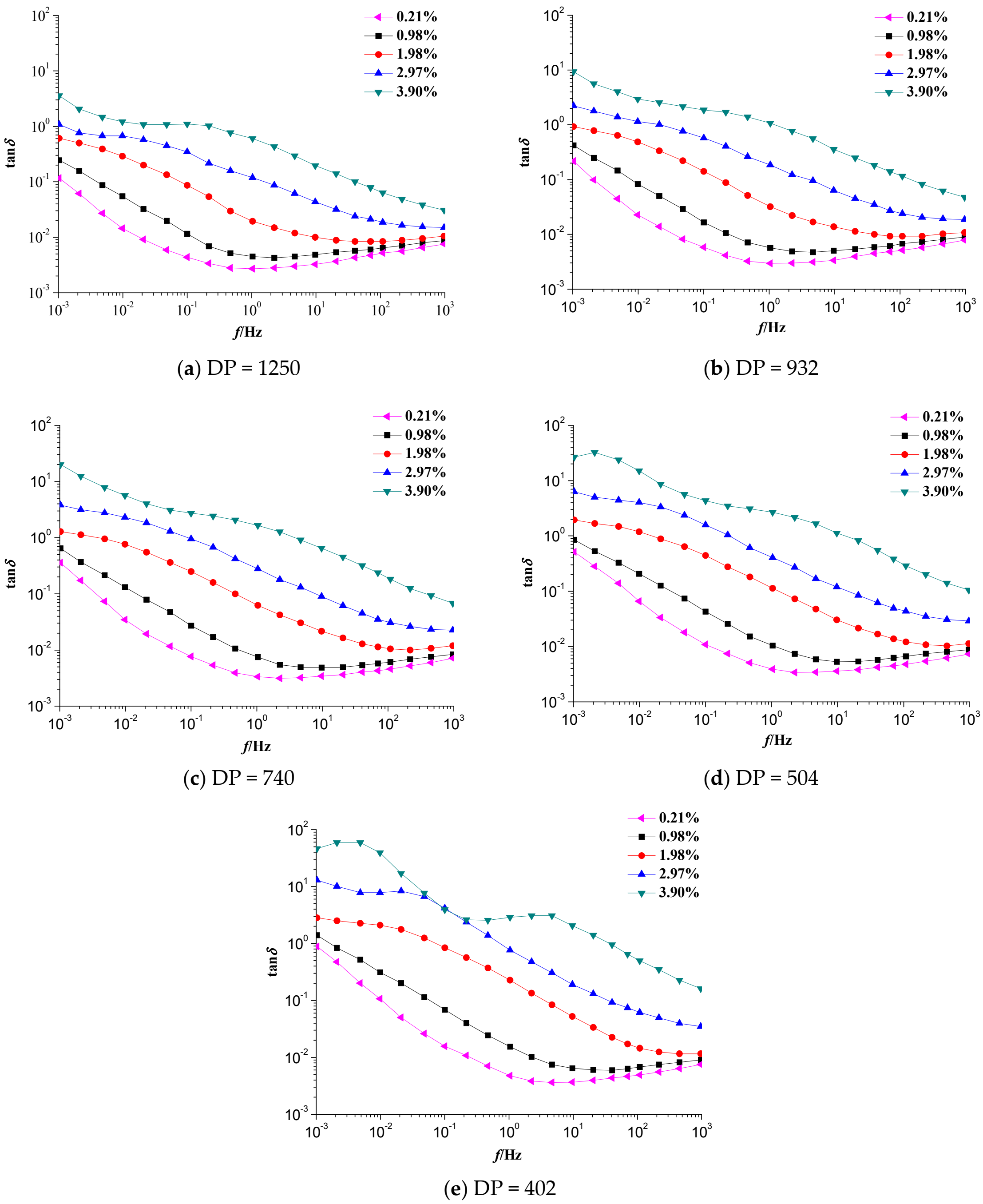
(**c**) MC 1.98% (**d**) MC 2.97%

(**e**) MC 3.90%

Figure 2. The tanδ curve of samples under different aging degree in set A~E.

While, when moisture content reaches a high-level (shown in Figure 2c–e), there are some laws which are ignored in previous studies. It is considered in the literature [23,24] that the aging only affects the low-frequency range, but with the increase of moisture content, the influence of aging degree on tanδ curve increases gradually under the same moisture content. This shows that the impact of aging and moisture on tanδ is not only a single effect, but an interactional process. Especially in the higher moisture content, the influence of aging on the tanδ curve will be greatly promoted by moisture. So, the influence between moisture and aging cannot be ignored when characteristic parameters were extracted from this band for condition evaluation.

Figure 3 is the tanδ curve with different moisture content at the same aging degree, which can be transformed from Figure 2. According to the literature [24,27], moisture has a greater impact on the tanδ value in a high-frequency range. In the range of 10^{-3}~10^{-1} Hz, comparing the tanδ curves of sample D_0 and A_3 with sample D_3, it can be seen that the influence of moisture and aging on tanδ is more complicated rather than simple superposition [23]. Therefore, in evaluating aging degree and moisture content, the assessment method can not only take individual factors into account while ignoring the impact between the two. Because when measuring moisture or aging, if no measures are taken to eliminate the interactions mentioned above, the measuring results are bound to be disturbed by each other and neither of them can be accurately evaluated.



(a) DP = 1250
(b) DP = 932
(c) DP = 740
(d) DP = 504
(e) DP = 402

Figure 3. The tanδ curve of samples under different moisture content in set A~E.

3.2. Extraction of Moisture and Aging Characteristic Parameters

From the above analysis, it can be seen that the influence of moisture and aging on the frequency band of tanδ curve are totally different. In the range of 10^1~10^3 Hz, the tanδ curves are mainly affected by moisture content, while aging degree has little effect. For dry oil-paper insulation samples (Figure 2a), tanδ curves reflect the aging degree well in the range of 10^{-3}~10^{-1} Hz. Therefore, S_m (the frequency integral value of tanδ from 10^1 to 10^3 Hz) is extracted as the characteristic parameter for characterizing the moisture content, and S_{DP} (the frequency integral value of tanδ from 10^{-3} to 10^{-1} Hz) is extracted as the characteristic parameter for evaluating the aging degree, as shown in Equations (4) and (5).

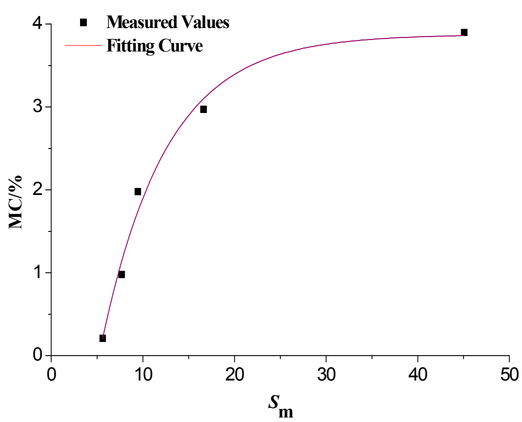
$$S_m = \int_{10^1}^{10^3} \tan\delta \, df \tag{4}$$

$$S_{DP} = \int_{10^{-3}}^{10^{-1}} \tan\delta \, df \tag{5}$$

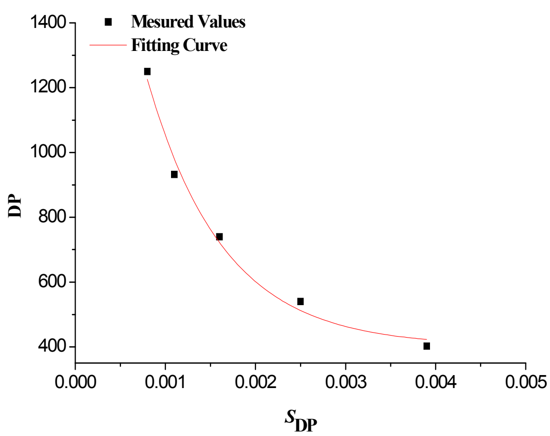
Figure 2a presents the tanδ curve corresponding to the different aging degree of the dry samples. Figure 3a shows the tanδ curve of the unaged samples under different moisture content. In order to explore the relationship between single factor and characteristic parameters, the characteristic parameters S_m and S_{DP} are fitted with moisture content and aging degree according to Figures 2a and 3a. Table 3 gives the fitting equation and the fitting parameters, Figure 4 is the fitting curve. MC and S_m, DP and S_{DP} have excellent fitting goodness of index.

Table 3. The fitting Equation of S_m and S_{DP}.

Fitting Parameters	Fitting Equation Y = A + B*exp (C*x)	R^2
MC vs. S_m	MC = 3.874−8.093*exp (−0.1411*S_m)	0.9886
DP vs. S_{DP}	DP = 401.3 + 2113*exp (−1178*S_{DP})	0.9903



(**a**) MC vs S_m



(**b**) DP vs S_{DP}

Figure 4. Fitting curves between characteristics and oil-paper stutas.

For dry insulation samples, S_{DP} can well reflect the aging degree of insulation paper. Similarly, S_m has a strong relationship with MC of unaged insulation paper. However, moisture has an effect on the tanδ curve in the whole measurement frequency range, and the moisture content in insulation paper will cause the S_{DP} increase, resulting in the evaluation of aging degree being overestimated. In the frequency range of 10^1~10^3 H_Z, the tanδ curve will be affected by aging degree in high moisture level. Therefore, using the above characteristic parameters to evaluate aging and moisture will be affected which results in the assessment results not being completely reliable. So, in order to eliminate the impact, the problem will be further studied in the next section.

3.3. Compensation Factor of Charicteristic Parameter

3.3.1. Moisture Compensation Factor

The aging degree of insulating paper mainly affects the low-frequency range of the tanδ curve, while moisture content has an influence on tanδ curve in the whole frequency range. Therefore, in the evaluation of insulation aging degree, the influence caused by moisture cannot be ignored. So, in order to improve the evaluation precision of aging degree of insulating paper, in this section, the aging characteristic parameter S_{DP} is modified to eliminate the influence caused by moisture, as shown in Equation (6).

$$S_{DP} = S\prime_{DP} - \beta = \int_{10^{-3}}^{10^{-1}} \tan\delta \, df - \beta \tag{6}$$

In Equation (6), β is the increased value of S_{DP} caused by the moisture in insulating paper relative to the dry insulating paper. S'_{DP} is the measured value which includes the effect of moisture content on tanδ curve. The value of β is related to the aging degree and moisture content of oil-paper insulation.

In order to quantify the effect of moisture on aging degree, the moisture compensation factor (MCF) γ is defined as Equation (7). The value of γ indicates the influence ratio of moisture content on aging degree based on tanδ curves in oil-paper insulation. Figure 5 illustrates the meaning of MCF with B_1 and B_3 samples.

$$\gamma = \frac{\beta}{S_{DP}} = \frac{S\prime_{DP} - S_{DP}}{S_{DP}} \tag{7}$$

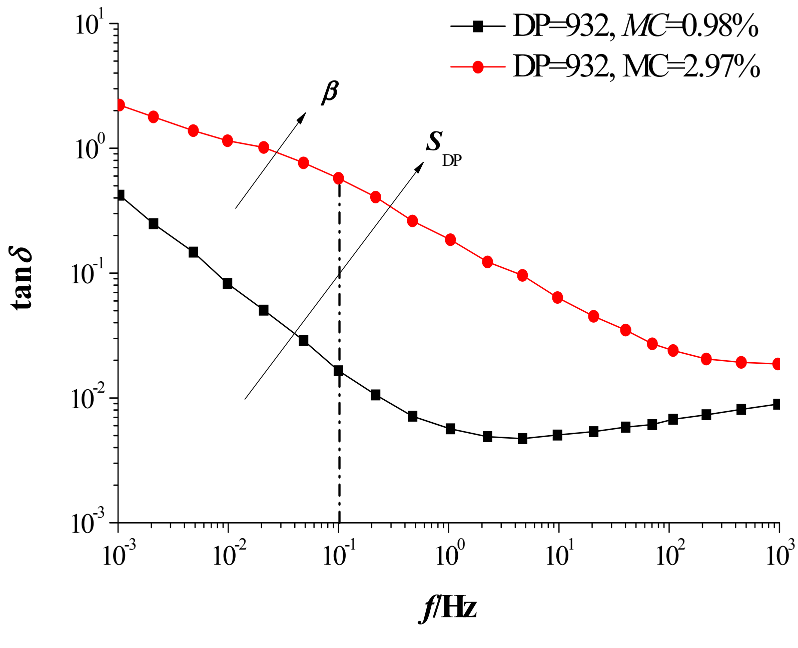


Figure 5. Description of moisture compensation factor.

Table 4 presents the value of MCF under different aging degrees. It can be seen from the MCF of A~E sets that MCF augments rapidly with the increase of moisture content while slowly with the increase of aging degree. This indicates that the moisture content in the insulating paper has a prominent effect on S_{DP}, and the higher the moisture content is, the more inaccurate the evaluation of aging degree of insulating paper will be. When moisture content of the insulating paper reaches 1%, S_{DP} increases to double of the dry insulating paper, which affects the assessment accuracy of aging degree. When moisture content exceeds 2%, S_{DP} is invalid to evaluate aging degree.

Table 4. Moisture compensation factor γ form set A~E.

DP \ MC/%		0.21	0.98	1.98	2.97	3.98
1250	β	0	0.0019	0.0154	0.0471	0.1143
	γ	0	2.3795	19.2866	58.9871	143.1470
932	β	0	0.0028	0.0257	0.0827	0.2402
	γ	0	2.3333	21.4167	68.9167	200.1667
740	β	0	0.0042	0.0419	0.1473	0.3848
	γ	0	2.6250	26.1875	92.0625	240.5000
504	β	0	0.0066	0.0695	0.2563	0.7406
	γ	0	2.6400	27.8000	102.52	296.2400
402	β	0	0.0102	0.1322	0.6275	1.2730
	γ	0	2.6154	34.1538	160.8974	326.4103

In order to find the optimal fitting relationship among the parameters, MCF, DP and MC were fitted by three-dimensional interpolation. The three-dimensional interpolation fitting surface is shown in Figure 6. From the fitting surface, the increase tendency of MCF can be seen when aging degree and moisture content increase. Figure 6 also shows that aging and moisture are not simply superimposed, and the interaction between them is more serious in the high moisture content and aging degree range. Under the premise of given aging degree and moisture content, the moisture compensation factor has a unique value which can be solved by interpolation function. Thus, using the obtained MCF γ to eliminate the characteristic S_{DP} can acquire the accurate result of DP. In this paper, matlab interpolation function toolbox is used for fitting and calculation.

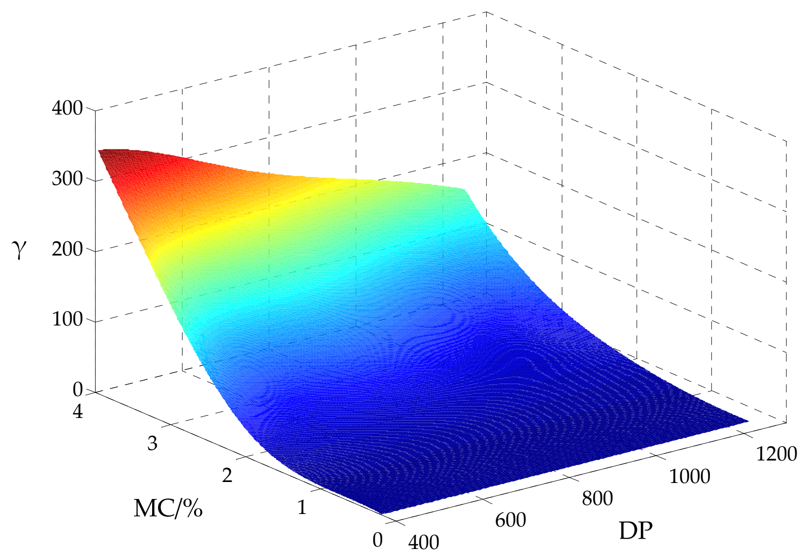


Figure 6. Fitting surface of moisture compensation factor.

3.3.2. Aging Compensation Factor

Although aging degree has little impact on tanδ in range 10^1~10^3 Hz, when moisture content reaches a high-level, the effect of aging on this band has become obvious. Therefore, with moisture content increasing, the influence caused by aging degree cannot be ignored. So, the characteristic S_m is modified to eliminate the influence of aging degree. The modified S_m is as shown in Equation (8).

$$S_m = S'_m - \lambda = \int_{10^1}^{10^3} \tan\delta \, df - \lambda \tag{8}$$

In Equation (8), λ is the increased value of S_m caused by the aging degree in insulating paper relative to the unaged insulating paper in frequency 10^1~10^3 Hz. S'_m is the measured value which including the effect of aging degree on tanδ curve. The value of λ is related to the aging degree and moisture content of insulating paper. In order to quantify the effect of aging degree on moisture content of oil-paper insulation, the aging compensation factor (ACF) ϕ is defined as Equation (9). Figure 7 illustrates the meaning of ACF with D_0 and D_3 samples.

$$\phi = \frac{\lambda}{S_m} = \frac{S'_m - S_m}{S_m} \tag{9}$$

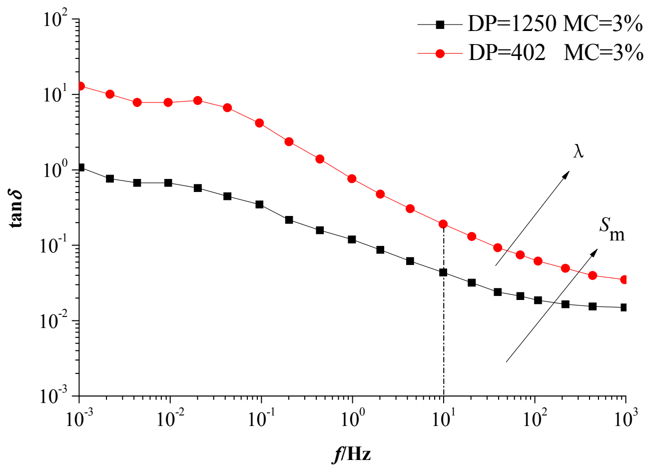


Figure 7. Description of aging compensation factor.

Table 5 presents the value of ACF under different moisture content. It can be seen that the ACF increases with the aging degree and moisture content of insulating paper. When the moisture content is less than 1%, the maximum ACF is 0.13, which has little effect on measurement of moisture content. While when moisture content exceeds 2%, the overall ACF is higher than 1, the maximum can reach 5. This indicates that when moisture content is high, the effect of aging on moisture become obvious which is consistent with previous analysis of tanδ curve in Section 3.1.

Table 5. Aging compensation factor ϕ form set A~ E.

MC/% \ DP		1250	932	740	504	402
0.21	λ	0	0.1504	0.2425	0.5618	0.6318
	ϕ	0	0.0268	0.0433	0.0904	0.1127
0.98	λ	0	0.3464	0.4979	0.7367	0.9507
	ϕ	0	0.0472	0.0678	0.1004	0.1295
1.97	λ	0	0.1333	1.5339	2.2930	3.2919
	ϕ	0	0.0141	0.1624	0.2427	0.3485
2.98	λ	0	4.3835	9.6196	18.3301	29.9635
	ϕ	0	0.2639	0.5792	1.1036	1.8040
3.90	λ	0	29.1500	68.9005	136.4022	250.3395
	ϕ	0	0.6469	1.5290	3.0269	5.5554

Similar to Section 3.1, MFC, DP and MC were fitted by three-dimensional interpolation. The three-dimensional interpolation fitting surface is shown in Figure 8. The fitting surface reflects the relationship among the parameters. It can be clearly seen that the influence ratio of aging degree is not obvious in regions with low moisture content (under 2%), while ACF increases rapidly in the high moisture range (over 2 %). Under the premise of given aging degree and moisture content, the aging compensation factor has a unique value, which can be solved by interpolation function. Thus, the accurate result of moisture content can be acquired after using the obtained ACF ϕ to compensate the characteristic S_m.

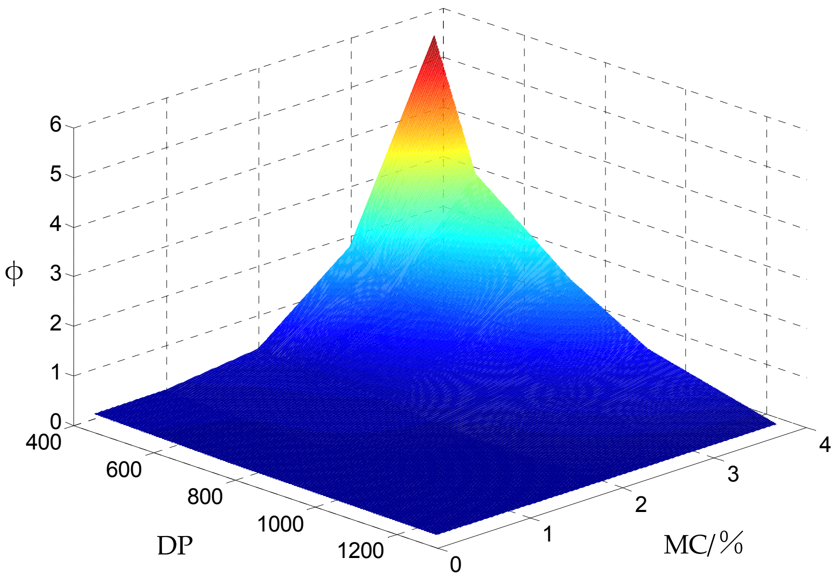


Figure 8. Fitting surface of aging compensation factor.

4. A New Approach to Assessing Aging Degree of Oil-Paper Insulation

The above compensation factors can eliminate one element of aging and moisture when evaluating the other, but the disadvantage is that the specific values of factors need to be obtained (MC value or DP value). However, it is often difficult to get any precise value of the two. Therefore, an algorithm is proposed to solve this problem, specific steps are as follows:

(1) Firstly, the tanδ curve of oil-paper insulation sample is measured, and S_{DP}, S_m are calculated by tanδ curve. According to fitting Equation in Table 3, moisture content can be obtained, and the results are recorded as MC_0. As the impact of moisture on aging measurement is noteworthy, according to DL/T984-2005 <oil-immersed transformer insulation aging guidelines> [28], the range of DP can be obtained through the transformer operating years, and recorded as DP_0. MC_0, and DP_0 are taken as initial value, but both have errors.

(2) The DP value and MC value of steps 1 are brought into the ACF surface to calculate ACF ϕ. Then, S_m is modified by ϕ, and the modified S_m is brought into the table 3 to obtain the new MC′. Finally, the S_m compensating operation is repeated until the difference of the two adjacent moisture calculation results less than 1%.

(3) The DP value and MC value of steps 2 are brought into the MCF surface to calculate MCF γ. Then, S_{DP} is modified by γ, and the modified S_{DP} is brought into the Table 3 to obtain the new DP′. Finally, the S_{DP} compensating operation is repeated until the difference of the two adjacent DP calculation results less than 1%.

(4) If DP and MC meet the condition of $(DP_j - DP_{j-1})/DP_{j-1} < 1\%$ and $(MC_i - MC_{i-1})/MC_{i-1} < 1\%$, the DP and MC can be used as evaluation results. Otherwise, repeat steps 2, 3.

This method uses the compensation factor surface to approximate the true compensation factor step by step. Finally, the effect of moisture or aging on the measurement in S_{DP} and S_m is eliminated, and the accurate evaluation results are obtained according to Section 3.2. The flow chart of compensation factor method is shown in Figure 9.

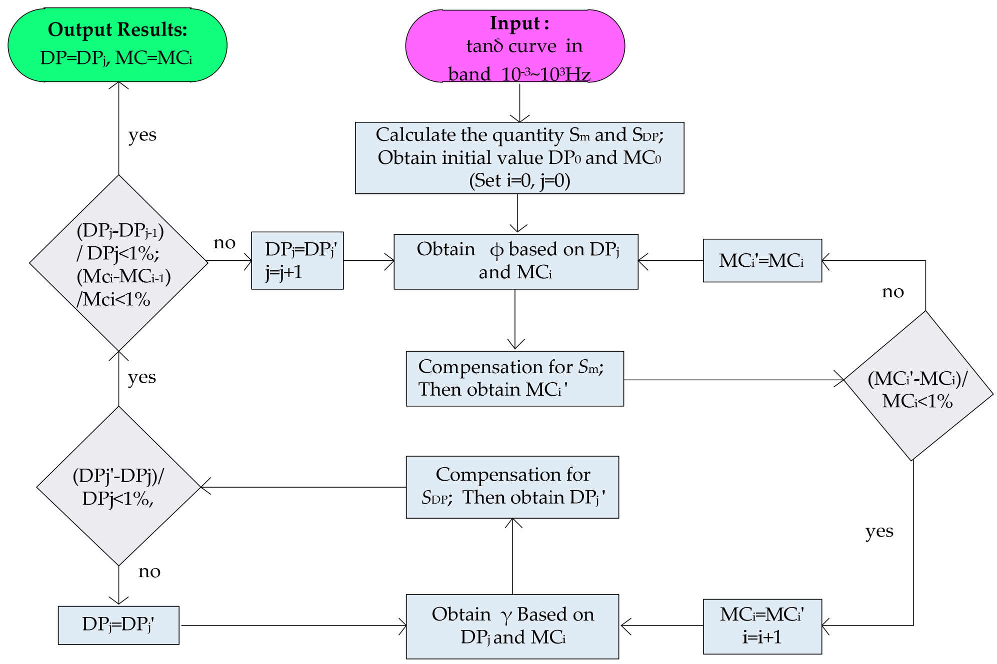


Figure 9. The flow for condition assessment of oil-paper insulation by Compensation factor algorithm.

5. Field Test

In order to verify the feasibility of the compensation factor method to evaluate aging degree and moisture content in the main insulation of field transformers, in this section, two 110 kV double-winding transformers with different operating times in different regions (Sichuan, China) Power Grid Company were used as examples to evaluate the main insulation status. The specific information of transformers for field test is shown in Table 6.

Table 6. Specific information of field transformers.

Number	Voltage Level	Rated Capacity	Put into Operation Time	Testing Oil Temperature
1#	110 kV	40,000 kVA	2008.02	26 °C
2#	110 kV	31,500 kVA	1997.09	28 °C

IDAX300 dielectric response analyzer was selected as field test instrument, the test frequency was set in the range of 10^{-3} to 10^{3} Hz and the test voltage peak was set to 200V. At the beginning of test, top oil temperature of 1# transformer was 26 °C, top oil temperature of 2# transformer was 28 °C. The fluctuation of the oil temperature of the two transformers was less than 2 °C during the whole test. According to temperature shift method and XY model of oil-paper insulation in the references [24,29], the FDS curve of field transformers had been adjusted by temperature shift, so as to obtain tanδ curves at reference temperature 30 °C, as shown in Figure 10.

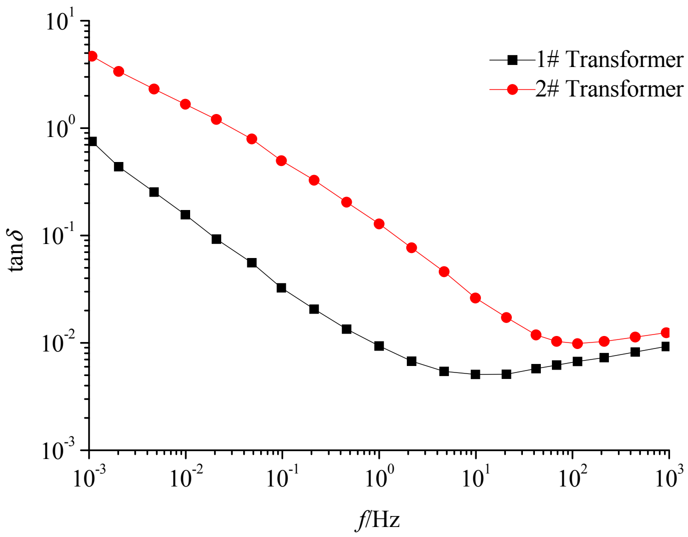


Figure 10. The tanδ curves of field transformers.

Referring to DL/T984-2005<oil-immersed transformer insulation aging guidelines>, 1# transformer has served for 10 years, which is in the middle of aging; 2# transformer has served for 18 years, the main insulation DP less than 500 which is in the late aging stage. So, the initial value of the 1# transformer was chosen as DP_0 = 700, and the initial value of the 2# transformer was chosen as DP_0 = 500. Table 7 shows the evaluation results of the compensation factor method for the insulation state of field transformers. 1# transformer status evaluation results are DP = 771.9, MC = 1.015%; 2# transformer evaluation results are DP = 446.7, MC = 1.644%. The MC results are similar to IDAX300's results, and shown in Table 7. Since it is not possible to sample the field transformer, so the exact value of DP is unknown, but the DP results of compensation factor method are in a reasonable range.

Table 7. Field transformer insulation state evaluation results based on compensation factor.

Transformer Number	1#		2#	
Characteristics Quantity	$S'_{DP} = 6.43 \times 10^{-3}$	$S'_m = 7.8692$	$S'_{DP} = 0.0741$	$S'_m = 11.3092$
Steps	DP_0 = 700 DP_1 = 714.3901 DP_2 = 735.5002 DP_3 = 749.5591 DP_4 = 760.4752 DP_5 = 768.7620 DP_6 = 771.9256	MC_0 = 1.2078% MC_1 = 0.9944% MC_2 = 1.0005% MC_3 = 1.0058% MC_4 = 1.0094% MC_5 = 1.0123% MC_6 = 1.0153%	DP_0 = 500 DP_1 = 459.8575 DP_2 = 452.8577 DP_3 = 448.0983 DP_4 = 446.7295	MC_0 = 2.2331% MC_1 = 1.7165% MC_2 = 1.6754% MC_3 = 1.6497% MC_4 = 1.6439%
Results	DP = 771.9	MC = 1.015%	DP = 446.7	MC = 1.644%
IDAX300	-	MC = 1.10%	-	MC = 1.59%

6. Conclusions

In this study, Oil-paper insulation samples were prepared through an accelerated thermal aging test. After aging, samples were dried and the DP of them were measured. Then, different moisture content samples (0%~4%) were obtained under each aging degree with natural moisture absorption. The dielectric loss (tanδ) curves of oil-paper insulation under different conditions were measured based on the FDS measurement. By analysis of curves, the characteristic parameters of aging and moisture were proposed, and the compensation factor and compensation factor evaluation algorithm were put forward for compensating the influence on characteristic parameters and accuracy of evaluating the condition of oil-paper insulation.

From the tests, when the moisture content is less than 2%, the range of 10^1~10^3 Hz is mainly affected by moisture content and aging degree has little effect. While when moisture content exceeds 2%, the effect of aging degree on this band became increasingly prominent. In conclusion, consistent with previously published literatures, aging degree mainly affects low-frequency range (10^{-1}~10^{-3} Hz) of tanδ curve and moisture mainly affects high-frequency range (10^1~10^3 Hz) of the tanδ curve, and meanwhile the effects of aging and moisture on high-frequency or low-frequency bands cannot be ignored. The effects of aging and moisture on the FDS curve interact with each other. When moisture content is higher or aging is more serious, the degree of mutual interference is even greater. Moreover, the integral values S_m (10^1~10^3 Hz) and S_{DP} (10^{-3}~10^{-1} Hz) were proposed as characteristic parameters of moisture content and aging degree respectively, which have excellent fitting relationship with moisture and aging degree of oil-paper insulation. The compensation factor ϕ was proposed for compensating the effect of aging on S_m and the compensation factor γ was proposed for compensating the effect of moisture on S_{DP}. The compensation factors can eliminate one element of aging and moisture when evaluating the other. Finally, a new method was proposed to evaluate the oil-paper insulation condition based on the aging and moisture content compensation factors, which can eliminate the influence between aging and moisture, and its validity were preliminarily verified by field transformers.

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