Normalization for FDS of Transformer Insulation Considering the Synergistic Effect Generated by Temperature and Moisture

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ABSTRACT

Frequency domain spectroscopy (FDS) technique is widely applied in the condition assessment of the oil-paper system in power transformers. However, the synergistic effect generated by moisture and temperature on the FDS data cannot be analyzed by the existing model since the single independent variable (moisture or temperature) is considered in the construction of the model. To quantify such the synergistic effect, a novel method that utilized for normalizing (or standardizing) the FDS curve is reported based on the theory of the power series and fitting analysis. The present findings reveal that the reported method is capable of predicting the dielectric loss (tanδ) curve under diverse test conditions, in which the average error is less than 7%. The synergistic effect can be also explored by using the extracted feature parameters. The potential application is then proved to make up for the measurement errors during the FDS test, the findings are expected to promote the moisture analysis of the transformer insulation.

INDEX TERMS

Transformer, oil-paper insulation, frequency domain spectroscopy (FDS), moisture, temperature effect.

I. INTRODUCTION

The oil-paper system, as the main high-voltage insulation system inside power transformers, will be gradually aged in the long-term service due to the influence of multiple stresses, such as thermal field and electric field [1], [2]. It is a fact that the deterioration (aging or damp) of insulating oil can be improved/restored by filtering or changing oil [3], while the deterioration of insulation paper/pressboard is irreversible. Therefore, the service life of the transformer oil-paper system mainly depends on the deterioration degree of oil-immersed paper/pressboard [4]–[6].

Reviewing the existing researches, the approaches for state evaluation and condition monitor of transformer cellulose insulation have been widely reported. The typical analysis method is constituted of direct measurement (including the degree of polymerization [7], tensile strength [8], and Karl Fischer titration [9]), dissolved chemical indicators in the oil (dissolved gas [10], acid, aldehyde [11], furfural [12]), electrical indicators (insulation resistance, absorption ratio [13]), the theory of chemical reaction kinetics (aging kinetics model [14]–[16]), and especially dielectric response technique (time-domain response [17], [18] and frequency-domain spectroscopy, FDS [19], [20]). Relying on the strong anti-interference and the rich insulation information, the FDS is thus of great interest to the scholars in lab or field conditions [4].

The published researches [21]–[23] indicated that the crucial factors affecting the FDS test mainly include insulation geometry, test voltage, moisture, the conductivity of insulation, and temperature. It is pointed out that the contribution of moisture and temperature to the FDS would be inevitably contained in the collected FDS [24], [25]. In this case, the results of the condition evaluation of transformer...
insulation will be unreliable once the mentioned synergistic effect generated by moisture and temperature on the collected FDS is ignored.

Provided that the FDS data can be simulated (or normalized) by the defined parameters contained in the equivalent models (or equations), the quantitative analysis of the synergistic effect generated by moisture and temperature on the FDS data can be realized. However, the mentioned synergistic effect cannot be analyzed by using the existing model, since merely the single independent variable (moisture or temperature) has been considered in the construction of the model [26]–[28]. Moreover, the analysis results of the same FDS data obtained by the various individual would be distinguished due to the complexity of the fitting process and the dependence of the fitting algorithm. Thus, the existing models are considered difficult to realize the general normalization of the FDS.

In view of the above issues, depending on the theory of the power series [29], a novel method that utilized for normalizing the FDS curve of transformer oil-immersed insulation is reported. The present findings reveal that the reported method is capable of predicting the dielectric loss (\(\tan \delta\)) curve under diverse test conditions, the obtained average error is less than 7%. Also, the synergistic effect can be studied by using the extracted feature parameters. The attached potential ability is then proved to make up for the measurement errors during the FDS test. In that respect, the present contributions are expected to promote the moisture analysis of the transformer insulation.

II. EXPERIMENTAL SCHEME AND FDS TEST
A. EXPERIMENTAL MATERIALS AND SCHEME

In this work, the mineral insulating oil and cellulose pressboard were employed to prepare oil-immersed pressboards. Specifically, the cellulose pressboard is manufactured by Taizhou Weidmann High Voltage Insulation Co., Ltd. The insulating oil is manufactured by Sinopec Group. The pictures and details of the non-aged materials are shown in Figure 1. The scheme for sample preparation can be found as follows.

i Pretreatment: first, the oil and pressboards were respectively dried and degassed in a ‘vacuum drying oven’ (as shown in Figure 2) for 48 h at 105 °C/50 Pa.

ii Immersion: Then, the pressboards were immersed with degassed and dried mineral insulating oil with a weight ratio of 20:1 last for 48 h at 60 °C/50 Pa to obtained the oil-immersed cellulose pressboard.

iii Moisture absorption: The oil-immersed cellulose pressboard with initial moisture content \(a\)% is placed in a precision electronic balance and its quality \(m\) is recorded, the natural moisture absorption is later performed to obtain the pressboard with various expected \(m_c\)%.

iv Equilibrium: Finally, the equilibrium of the moisture is performed for 48 h at 45 °C before the FDS test.

In this work, the moisture is measured by the Metrohm Coulomb Karl Moisture Tester (831+885) based on IEC 60814. Five sets of experiments by adopting the prepared samples with various moisture were designed, by which the model construction (in chapter III), model verification (in chapter IV), and model discussion (in chapter V) are performed, respectively. The details of these experiments are shown in Table 1.

B. THE PLATFORM OF FDS TEST

The dielectric response test was performed under the help of the device, including the DIRANA/OMICRON and a three-electrode test cell, as is shown in Figure 3. Where, the higher the output voltage, the stronger the anti-interference ability, thus, the amplitude of the output voltage, i.e. 200 V is selected. The available measurement regions are \(1 \times 10^{-4}\) to 5000 Hz. However, the lower the measurement frequency, the longer the measurement time. Thus, the frequency region of \(4 \times 10^{-4}\) to 5000 Hz is selected. In Figure 3, the three-electrode system should be arranged with a constant temperature (45 °C in this work).
when performing the FDS test. Besides, the electromagnetic noise should be shielded as much as possible. The metallic shield could be serviced as an available way.

III. THE MODEL FOR NORMALIZING THE FDS CURVE

Relying on the fitting analysis of the FDS by using the defined formulas, a set of equations and its parameter can be obtained, so that the FDS data can be simulated (or represented) by these defined parameters. Such the process is defined as the normalization (or standardization) of FDS curves. Therefore, the model, utilized for predicting the FDS data under the various test conditions, is constructed in this work by using the theory of power series.

A. THE FORMULA FOR NORMALIZING THE FDS CURVE

Assuming that $\tan\delta_1(\omega)$, $\tan\delta_2(\omega)$, ..., $\tan\delta_n(\omega)$ belong to the sub relaxation response function of the total frequency response function $\tan\delta(\omega)$, which is defined in the frequency interval $I \in (f_a, f_b)$, then, this property can be written as Equation (1).

$$
\tan \delta(\omega) = \tan \delta_0(\omega) + \tan \delta_1(\omega) + \cdots + \tan \delta_n(\omega)
= \sum_{n=0}^{\infty} \tan \delta_n(\omega)
$$

(1)

If both the sub relaxation $\tan\delta_n(\omega)$ in Equation (1) can be linked by the power functions that defined in the interval $I$, then Equation (1) can be revised as Equation (2).

$$
\tan \delta(\omega) = \Phi_0 + \Phi_1 \cdot (\omega - \omega_0) + \Phi_2 \cdot (\omega - \omega_0)^2
+ \cdots + \Phi_n \cdot (\omega - \omega_0)^n
= \sum_{n=0}^{\infty} \Phi_n \cdot (\omega - \omega_0)^n
$$

(2)

where, $n$ is series of function terms, $\omega$ is the angular frequency, $\Phi_0$ is the intercept of power functions, the $\Phi_i(i = 1, 2, \ldots, n)$ is defined as the coefficient of each sub relaxation function. Thus, the total frequency response function $\tan\delta(\omega)$ can be regarded as the power series in the interval $I \in (f_a, f_b)$. Especially, if the $\omega_0$ presented in Equation (2) is equal to 0, its formula can be obtained.

$$
\tan \delta(\omega) = \Phi_0 + \Phi_1 \cdot \omega + \Phi_2 \cdot \omega^2 + \cdots + \Phi_n \cdot \omega^n
= \sum_{n=0}^{\infty} \Phi_n \cdot \omega^n
$$

(3)

From Equation (3), the $\tan\delta(\omega)$ can be equivalent to the superposition behavior of various sub relaxation function, which is related to the measurement frequency ($\omega = 2\pi f$). Such property can be also utilized to discuss the frequency-dependence [19] of the dielectric materials.

The dielectric loss of the same sample is not only related to the measurement frequency, but also distinctly affected by the insulation states (inside moisture) and test conditions (temperature). Consequently, the formula for modeling the frequency response characteristics by employing power series can be expressed as Equation (4) when considering the synergistic effect generated by moisture and temperature on the FDS.

$$
\tan \delta(\omega, T, mc\%) = \Phi_0(T, mc\%) + \Phi_1(T, mc\%) \cdot \omega + \cdots
+ \Phi_n(T, mc\%) \cdot \omega^n
= \sum_{n=0}^{\infty} \Phi_n(T, mc\%) \cdot \omega^n
$$

(4)

B. THE PARAMETERS IN THE NORMALIZED FDS CURVE

According to the interpretation of the normalization of the FDS curve in the previous chapter, the normalized FDS curve can be obtained by fitting analysis. When taking the experiment 1 to 3, the comparison of measured $\tan\delta$ curves and normalized $\tan\delta$ curves by using the Equation (4) can be plotted in Figure 4. The normalized curves and the measured values coincide in the whole frequency ranges under different test conditions. Also, the obtained parameters contained in Equation (4) are listed in Table 2.

| NO. | $T$(°C) | $\Phi_0$ | $\Phi_1$ | $\Phi_2$ | $\Phi_n$ | $R^2$ |
|-----|----------|----------|----------|----------|----------|-------|
| Exp.1 | 45       | 0.694    | -0.244   | 6.24E-2  | 1.38E-3  | 0.998 |
|      | 60       | 0.901    | -0.305   | 5.28E-2  | 5.85E-3  | 0.999 |
|      | 75       | 1.152    | -0.427   | 3.80E-2  | 7.56E-3  | 0.999 |
|      | 90       | 1.283    | -0.453   | 3.50E-2  | 8.40E-3  | 0.999 |
| Exp.2 | 45       | 1.124    | -0.352   | 3.50E-2  | 6.79E-3  | 0.999 |
|      | 60       | 1.357    | -0.398   | 2.41E-2  | 6.79E-3  | 0.999 |
|      | 75       | 1.615    | -0.402   | 1.55E-2  | 4.57E-3  | 0.999 |
|      | 90       | 1.757    | -0.406   | 1.32E-2  | 1.64E-3  | 0.999 |
| Exp.3 | 45       | 1.437    | -0.407   | 1.76E-2  | 9.41E-3  | 0.998 |
|      | 60       | 1.675    | -0.401   | 8.75E-3  | 5.59E-3  | 0.997 |
|      | 75       | 1.821    | -0.363   | 4.55E-3  | 1.28E-3  | 0.997 |
|      | 90       | 2.065    | -0.357   | 3.24E-3  | -6.50E-4 | 0.999 |

From Equation (3), the $\tan\delta(\omega)$ is utilized to represent the fitting goodness. The closer the value of $R^2$ to 1, the higher the accuracy of the fitting analysis. It is thus worth mention that Equation (4) can be applied to simulate the $\tan\delta$ curves under different test conditions when parameter $n$ equals 3. From Figure 4 and Table 2, the average value of $R^2$ is 0.999 when $n$ equals 3.
The additional experimental results show that the average value of $R^2$ is 0.994, 0.999, and 0.999 when $n$ equals 2, 4, and 6, respectively. Thus, it is found that the fitting goodness will increase with the increasing value of $n$, but it is still considered unworthy due to the accompanying uncertainty of fitting analysis.

From Table 2, it is obvious that the intercept of power functions ($\Phi_{0i}$) and the coefficient of each sub relaxation function $\Phi_{ij}$ ($i = 1, 2, 3; j = 0, 1, 2, 3$) of the same sample alter regularly with the increasing test temperature, which might be described by the exponential function. Parameters $i$ and $j$ represent the types of moisture and the coefficient, respectively. To verify this viewpoint, the fitting analysis is performed to study the variation law of $\Phi_{ij}$ vs temperature ($T$). The fitting curves are presented in Figure 5 (only the results of $\Phi_{1j}$ is presented), besides, the obtained equations for calculating the $\Phi_{ij}$ are tabulated in Table 3, which can be further used for predicting the contained parameters.

**IV. VERIFICATION OF THE REPORTED MODEL FOR NORMALIZING FDS CURVE**

**A. THE PREDICTION OF THE NORMALIZED FDS CURVE**

It is worth to note that the model coefficients $\Phi_{ij}$ ($j = 0, 1, 2, 3$) under different temperatures and moisture can be calculated by using Table 3, which means that the normalized FDS curves can be further calculated by using Equation (4). Such property promotes the construction of the model for predicting the normalized FDS curves under different test conditions.

Provided that the value range of the test temperature $T$ is 45-90 °C, and the step size is 5 °C, then substitute $T$ into the equation shown in Table 3, the parameters $\Phi_{ij}$ of each...
TABLE 4. The formulas for calculating the coefficients.

| $\Phi_{ij}(mc\%, T)$ | $Z_0$ | $Z_T$ | $Z_{mc\%}$ | $Z_i$ | $Z_{mc\%}^2$ | $Z_j$ | $Z_{mc\%}^3$ |
|----------------------|------|------|-----------|------|-----------|------|-----------|
| $Z_0$                | -0.878 | $Z_1$ | -5.50E-5  | $Z_4$ | $Z_7$      | $Z_8$ | $Z_{mc\%}$ |
| $Z_1$                | 2.12E-2 | $Z_2$ | -3.01E-2  | $Z_5$ | $Z_9$      | $Z_6$ | $Z_{mc\%}^2$ |
| $Z_2$                | 0.625  | $Z_3$ | $R^2$     | $Z_7$ | $Z_9$      | $Z_6$ | $Z_{mc\%}^3$ |

$\Phi_{ij}(mc\%, T) = \frac{Z_0 + Z_T \cdot Z_j + Z_{mc\%} + Z_i \cdot Z_T^2 + Z_4 \cdot Z_{mc\%}^3}{1 + Z_T + Z_{mc\%} + Z_i^2 + Z_7 \cdot Z_{mc\%} + Z_8 \cdot Z_{mc\%}^2}$

TABLE 5. The calculated values of the coefficients.

| Parameters ($\Phi_{ij}$) | $\Phi_{ij}$ |
|--------------------------|-------------|
| Pressboard 4 (0.93%)     | 0.940       |
| Pressboard 5 (1.33%)     | 1.144       |
| Pressboard 6 (2.79%)     | 1.755       |

$75^\circ C$ Pressboard 4 (0.93%) | 0.940 | 5.13E-2 | 8.00E-3 |
$90^\circ C$ Pressboard 5 (1.33%) | 1.144 | 4.00E-2 | 7.80E-3 |
$90^\circ C$ Pressboard 6 (2.79%) | 1.755 | 7.86E-2 | 2.48E-3 |
$75^\circ C$ Pressboard 4 (0.93%) | 0.940 | 4.37E-2 | 9.17E-3 |
$90^\circ C$ Pressboard 5 (1.33%) | 1.144 | 3.30E-2 | 7.96E-3 |
$90^\circ C$ Pressboard 6 (2.79%) | 1.755 | 3.38E-2 | 1.77E-4 |

The calculation process for various moisture (0.93%, 1.33%, and 2.79%) are selected as the research object. The steps are as follows:

i. First, the FDS test of pressboard 4 to 6 at 75 $^\circ C$ and 90 $^\circ C$ is carried out, respectively.

ii. Then, measured $\tan\delta$ curves are obtained, meanwhile, the corresponding temperature and moisture are substituted into the equations shown in Table 4 to calculate the relevant parameters $\Phi_{ij}$, the calculated values are shown in Table 5.

iii. Finally, the $\tan\delta$ curve at the same test conditions is obtained by substituting the parameters $\Phi_{ij}$ into Equation (4). The comparison of measured values and predicted curves of pressboard 4 to 6 is drawn in Figure 7.

Depend on the observation of the measured values and the predicted curves in Figure 7, the two curves almost coincide in the full frequency ranges. In order to quantitatively analyze the error between the predicted value and the measured value, the relative error (R.E.) analysis is later carried out. The calculated results are presented in Figure 8. Equation (5) is utilized to calculate the R.E. of the prediction results point by point.

\[
\text{R.E} \text{(%)} = \frac{|\text{Measured } \tan\delta(f) - \text{Predicted } \tan\delta(f)|}{\text{Measured } \tan\delta(f)} \times 100\%
\]

where, the maximum/minimum value of the R.E. on 132 measurement frequency points is 28.42%/0.51%, the average values of R.E. at 75 $^\circ C$ and 90 $^\circ C$ are 6.59% and 6.51%, respectively. The mentioned error could be attributed to several factors. First, the calculation error of fitting analysis will be produced when building the functional relationship of extracted parameters versus moisture and temperature. Second, the measurement error could be inevitably contained in the FDS test. Thus, it might lead to the relative error of several points is much higher than others. Fortunately, the obtained results proved that the mentioned error will not sharply reduce the precision of the prediction result of dielectric loss curves.

V. DISCUSSION
A. POTENTIAL APPLICATION

In order to verify the feasibility and accuracy of the proposed method for predicting the FDS curves, the newly prepared pressboard 4 to 6 (shown in Table 1, experiment 4) with experiment at different temperatures can be calculated. In addition to the temperature effect, it can be observed from Table 3 that the $\Phi_{ij}(j = 0, 1, 2, 3)$ shows an exponential variation trend with the changing moisture. In order to demonstrate this viewpoint, the variation law among $T$, $mc\%$, and $\Phi_{ij}$ is studied by using fitting analysis.

Provided that the temperature ($T$), moisture ($mc\%$), and parameters ($\Phi_{ij}$) can be represented by the $X$, $Y$, and $Z$-axis in the same coordinate system, respectively, these values thus can be plotted on the same three-dimensional system. Then, a smooth surface can be gradually generated until the numbers of points are connected, the resulting Figure 6 thus can be used to examine the variation law among $T$, $mc\%$, and $\Phi_{ij}$ is studied by using fitting analysis.

The functional equation obtained by fitting analysis is regarded as an available model (shown in Table 4) for calculating the parameters $\Phi_{ij}$ of normalized $\tan\delta$ curve at diverse temperatures and moisture, respectively. Where, the parameters ($Z_0$ to $Z_9$) are the related constant. Therefore, the equation shown in Table 4 can be utilized as an available model for predicting the normalized $\tan\delta$ curve. The RSS is utilized to represent the residual sum of squares.

B. THE FEASIBILITY INVESTIGATION OF THE REPORTED MODEL FOR PREDICTING THE FDS CURVE

In order to verify the feasibility and accuracy of the proposed method for predicting the FDS curves, the newly prepared pressboard 4 to 6 (shown in Table 1, experiment 4) with several factors. First, the calculation error of fitting analysis will be produced when building the functional relationship of extracted parameters versus moisture and temperature. Second, the measurement error could be inevitably contained in the FDS test. Thus, it might lead to the relative error of several points is much higher than others. Fortunately, the obtained results proved that the mentioned error will not sharply reduce the precision of the prediction result of dielectric loss curves.
frequency range. Such the potential ability can not only be used to correct the accidental errors during the FDS test, but also to improve the test accuracy. Taking the tanδ curves of pressboard 4 (0.93%), pressboard 5 (1.33%), and pressboard 6 (2.79%) shown in Figure 7(a) as an example for proving the mentioned potential ability of the proposed method.

If the measurement fault or noise interference is generated and included in the process of FDS test, the measurement value in several frequency points might be unreliable. If these unreliable points are isolated from the other points, the region of data missing in the FDS curves will be generated immediately, as is shown in Figure 9(a). In this case, the collected FDS becomes unavailable for further analysis since it missing several measurement points. In order to solve this issue, the reported method can be readily applied to predict the original value in the region of data missing by using the remaining points, the results are shown in Figure 9(b). Besides, the FDS data was merely collected in several given points during the FDS test, while the FDS data corresponding to any frequency points can be predicted by using the proposed model, by which the predicted FDS data can form a continuous curve.

Besides, the proposed model can be also employed to explore both the temperature-dependence and moisture-dependence, which can be further used to correct the synergistic effect (generated by temperature and moisture) on the FDS data. Therefore, these contributions are expected to facilitate the assessment of the moisture inside the transformer oil-immersed cellulose insulation. Besides, reviewing the other kinds of dielectric response curves, including complex relative permittivity/capacitance, the observed property of frequency-dependence is similar to the research object discussed in this work, thus, the proposed model might available for analyzing the full dielectric response.

B. FURTHER ATTENTION

Whereas the moisture content in the main insulation system of field transformer is rather difficult to exceed 3% in the normal operation condition, the cellulose pressboards with moisture about (or less than) 3% are therefore prepared to explore its FDS. However, in terms of ‘extreme cases’, that defined as a case that the inside moisture high than 4%, it has not been considered. As mentioned above, the reported method is available for analyzing the FDS with the single
relaxation process, once the moisture is much higher than 3%, the relaxation process inside the dielectric becomes very complex and difficult to maintain a single relaxation state. Therefore, although the third-order model can be applied to most cases, the discussion of such ‘extreme cases’ is still considered interesting and necessary.

From Table 1, Experiment 5 is exactly prepared for discussing this issue. Figure 10(a) has presented the fitting results of ‘extreme cases’ by applying the three-orders power
series. Distinctly, the three-orders power function model cannot accurately simulate the tanδ curves under ‘extreme cases’ due to its complex relaxation process. Fortunately, this issue can be overcome by increasing its orders of power function model. Consequently, the fitting results of ‘extreme cases’ by applying the six-orders power series are drawn in Figure 10(b). The comparison of fitting goodness by using three-orders and six-orders of power series is tabulated in Table 6.

### VI. CONCLUSION

Depending on the analysis of the FDS by employing the equivalent model, the FDS under various test conditions can be normalized by defined parameters used in these models. Since this approach is beneficial to quantitative analysis of the frequency response characteristics, therefore, this work reported a novel method for performing the general normalization of the FDS curve. The present findings have led to the following conclusions.

i. The reported model can be utilized for normalizing (or standardizing) the dielectric loss (tanδ) curve of samples when its inside moisture less than 4%.

ii. The functional relationship among temperature, moisture, and the parameters contained in the power series is studied to obtain an available model for predicting the tanδ curve under different test conditions, the average error is then proved less than 7%.

iii. The potential application is proved to make up for the measurement errors during the FDS test, as well as explore the synergistic effect on FDS.

A universal conclusion or method might be derived from a large number of experiments. The reported fitting equations, models, and selected parameters significantly depend on individual materials. Therefore, given that the proposed method is supported to be applied to other test conditions, such as the samples with the various aging degrees, the contained parameters might be revised in advance. Further research could focus on this issue.

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