A Novel Curve Database for Moisture Evaluation of Transformer Oil-Immersed Cellulose Insulation Using FDS and Exponential Decay Model

JIEFENG LIU, (Member, IEEE), ZIXIAO WANG, XIANHAO FAN, (Student Member, IEEE), YIYI ZHANG, (Member, IEEE), AND JIAQI WANG

Guangxi Key Laboratory of Power System Optimization and Energy Technology, Guangxi University, Nanning 530004, China

Corresponding author: Yiyi Zhang (yiyizhang@gxu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61473272 and Grant 51867003, in part by the Natural Science Foundation of Guangxi under Grant 2018JBJ160064 and Grant 2018JJA160176, in part by the Guangxi Bagui Young Scholars Special Funding, in part by the Boshike Award Scheme for Young Innovative Talents, in part by the Guangxi Key Laboratory of Power System Optimization and Energy Technology Project under Grant AE3020001829, and in part by the Basic Ability Improvement Project for Young and Middle-aged Teachers in Universities of Guangxi under Grant 20190067 and Grant 20190046.

ABSTRACT

In recent decades, moisture evaluation of transformer oil-immersed cellulose insulation has been widely studied by using the frequency domain spectroscopy (FDS) technique. However, due to the difficulties in sample preparation, most of the existing evaluation methods are based on a small number of samples, which greatly limits the evaluation accuracy of these methods. To accurately evaluate moisture inside transformer oil-immersed cellulose insulation, a novel method combining the FDS technique and the exponential decay model is proposed. In current work, the exponential decay model is introduced to analyze the FDS data, which can be used to assess the quantitative relationship between moisture and extracted parameters. Then, the FDS curves with different moisture can be predicted by using these parameters to form a curve database. Findings reveal the relative error of evaluation results in lab condition is less than 10.57% when using the proposed curve database. In that respect, the feasibility of the proposed database is proved for moisture evaluation of transformer oil-immersed cellulose insulation.

INDEX TERMS

Power transformer, oil-immersed cellulose insulation, frequency domain spectroscopy (FDS), exponential decay model, moisture evaluation.

I. INTRODUCTION

The insulation performance of the oil-immersed power transformer affects the operation level of the power system. While the insulation performance is mainly determined by oil-paper insulation [1]. The deterioration of insulation oil can be solved by replacing oil and filtering oil, but no effective measures have been put forward to solve the deterioration of insulation paper (cellulose insulation). In this case, the service life of the transformer is mainly affected by the performance of oil-immersed cellulose insulation [2], [3].

According to researches [4]–[6], moisture is one of the main factors that degrade the oil-immersed cellulose insulation. Excessive moisture can seriously affect the dielectric properties, accelerate the aging process, shorten the insulation life, and decrease the partial-discharge inception voltage, etc. Therefore, it is of great significance to explore an effective method to accurately evaluate the moisture inside transformer oil-immersed cellulose insulation.

The insulation structure of the transformer will suffer irreversible damage when using the traditional Karl Fischer titration (KFT) [7]. It is thus impractical in field conditions. Conversely, the indirect method with the help of the cellulose-water adsorption isotherms could obtain the moisture inside cellulose without destroying the insulation [8]. Nonetheless, considering various factors such as temperature and equilibrium time, its uncertainty is as high as 200% [9]. In addition, online water activity probes have been developed and gradually applied [10]–[12]. The probe can measure the water activity of insulation oil, and the moisture in insulation paper can be continuously monitored by the Fessler model [13]. However, probes can only be installed during transformer
manufacturing or a major overhaul, which is unsuitable for in-service transformers. In recent years, regarding the demand for non-destructive and reliable evaluation of transformer oil-paper insulation, the dielectric response technique based on dielectric physics theory is thus proposed and utilized to realize this goal. The dielectric response technique can be divided into return voltage measurement (RVM) [14], [15], polarization/depolarization current (PDC) [15], [16] and frequency domain spectroscopy (FDS) [17], [18]. Compared with the RVM and the PDC, the FDS has a stronger anti-interference ability and can convey more insulation information [19]–[21]. Besides, the effect of temperature on FDS could be easily corrected using the “master curve” technique [22], [23]. Thus, FDS is regarded as a powerful tool for studying the moisture inside the transformer oil-immersed cellulose insulation.

Based on the FDS, early studies have explored the variation law generated by moisture. References [24], [25] pointed out that the FDS curves increase and move toward the high-frequency region as the moisture content increases. On this basis, present researches mainly focused on the extraction of the characteristic parameters from FDS curves [19], [26] or developing the equivalent circuit models (Cole-Cole model, Davidson-Cole model, etc.) [27], [28] for preliminary moisture evaluation. Grey correlation analysis [29], fuzzy pattern recognition [30], [31], and other methods were used to classify the insulation state of oil-immersed cellulose insulation. However, the evaluation accuracy of these methods highly depends on the number of the prepared sample. The evaluation accuracy and the application of these evaluation methods are limited by experimental conditions and measured error, preparation periods, and the number of samples.

In view of the above issues, a novel method for moisture evaluation based on the FDS technique is proposed. The moisture feature parameters can be readily extracted by using the FDS curve and exponential decay model. Then, the quantitative relationship between moisture and feature parameters is established to expand the ranges of parameters. Findings indicated that the FDS curves with various moisture can be predicted by using these feature parameters, then, the database of FDS curves used for moisture evaluation can be formed. Finally, moisture evaluation is performed and indicated that the relative error of the evaluation results is less than 10%, thus, it proved the accuracy and feasibility of the proposed database for moisture evaluation of transformer oil-immersed cellulose insulation.

II. EXPERIMENTAL DESIGN AND PLATFORM
A. THE PREPARATION OF OIL-IMMERSED PRESSBOARDS WITH VARIOUS MOISTURE CONTENT

This study aims to explore the moisture effect on the FDS of oil-immersed pressboard and establish a model to evaluate the moisture content ($mc\%$). Moreover, it should be emphasized that “$mc\%$” refers to the paper/pressboard moisture, rather than the oil moisture or the moisture in the whole insulation system. The ordinary pressboard discs (thickness: 1mm) and the mineral oil are used as experimental materials, and their specific relevant parameters are shown in Table 1.

To simulate the damp phenomenon caused by the invasion of moisture from the external environment, the moisture absorption experiment was performed on the oil-immersed pressboard. As shown in Fig. 1, it shows the main steps required for sample preparation, and more details are shown below:

i. **Pretreatment**: the fresh cellulosic pressboards and insulation oil were put into a vacuum tank with a ratio of 1:20. Then, vacuum drying (at 105°C and 50 Pa) and vacuum immersion (at 60°C and 50 Pa) were performed for each 48h successively. If the moisture content of the pressboard after these operations is less than 1%, the pretreatment is successful.

ii. **Moisture Absorption Experiment**: Firstly, clean the oil on the surface of the oil-immersed pressboard after step i). Afterwards, the oil-immersed pressboard with initial moisture content ($a\%$) was placed in a precision electronic balance to weigh the initial quality ($m_0$). Then, the natural moisture absorption in the open air was performed. Due to the ingress of moisture, the quality of the pressboard was increased under monitoring. When the quality of the pressboard with expected moisture content ($b\%$) was reached, moisture absorption would be stopped. After repeating the above experiment, a series of oil-immersed cellulose insulation samples with various moisture contents could be obtained. It is noted that the quality ($m$) of the pressboard with $b\%$ can be calculated by $m = m_0 \times (1 - a\%)/(1 - b\%)$.

| TABLE 1. The utilized materials for the preparation of oil-immersed cellulose pressboard. |
|-------------------------------|-----------------------------|
| Insulating oil                | Cellulose pressboard        |
| Type                          | Type                        |
| Karamay No.25 napthenic mineral oil | Ti, transformer pressboard |
| $\tan\delta$                  | Density                     |
| $4 \times 10^{-6}$            | 1.09 g/cm$^3$               |
| Pour point                    | Diameter                    |
| $\leq -45^\circ\mathrm{C}$    | 160mm                       |
| Flashpoint                    | Tensile strength            |
| $135^\circ\mathrm{C}$         | MD:105MPa                   |
|                              | strength                    |
|                              | CMD:80MPa                   |

FIGURE 1. The experimental design for samples preparation of oil-immersed pressboards and FDS test.
iii. **FDS Test**: When the moisture absorption experiment was completed, pressboards were immersed in 45°C insulation oil for 48 hours to achieve moisture equilibrium and keep stable at the FDS test temperature (45°C). After that, the FDS test was performed on each oil-immersed pressboard. More detailed information about the FDS test is shown in section II-B.

iv. **Moisture Test**: According to IEC 60814, the moisture content of each pressboard was tested by using a Karl-Fischer moisture meter. Three different parts of the pressboard are taken for each test, and the average test value is used as the measured moisture content of the pressboard.

In this study, 9 pieces of oil-immersed pressboards with different mc% were prepared and used for two experiments. One experiment aims to study the moisture-dependence of FDS curves and establish a model for evaluation, while the other experiment is designed to verify the established model. Detailed information for 9 pressboard samples and two designed experiments are illustrated in Table 2.

### TABLE 2. Samples of experiment and application.

| Experiments | Materials     | Measured mc% | Application       |
|-------------|---------------|---------------|-------------------|
| Experiment 1| Pressboard 1  | 0.91%         | Model Construction|
|             | Pressboard 2  | 1.31%         |                   |
|             | Pressboard 3  | 1.81%         |                   |
|             | Pressboard 4  | 2.47%         |                   |
|             | Pressboard 5  | 3.24%         |                   |
|             | Pressboard 6  | 3.84%         |                   |
| Experiment 2| Pressboard 7  | 0.73%         |                   |
|             | Pressboard 8  | 2.87%         | Model Verification|
|             | Pressboard 9  | 4.07%         |                   |

**FIGURE 2.** Schematic diagram of devices for FDS test.

**FIGURE 3.** The complex relative permittivity of oil-immersed pressboards with different mc%. (a) Real part $\varepsilon'(\omega)$; (b) Imaginary part $\varepsilon''(\omega)$.

Besides, the test type of the DIRANA tester was set to “FDS only” mode to obtain valid and accurate FDS data, that is, the FDS measurement was used in all frequency regions.

In order to ensure the accuracy of measurement, the FDS test was performed twice for each pressboard, and the average value was used for further analysis. The complex capacitance $C^*(\omega)$ can be directly obtained from the test, so the complex relative permittivity $\varepsilon^*(\omega)$ is easily calculated by the formula $\varepsilon^*(\omega) = C^*(\omega)/C_0$, where $C_0$ is the geometric capacitance. Based on the measurement data of FDS, the real part $\varepsilon'(\omega)$ and imaginary part $\varepsilon''(\omega)$ of the complex relative permittivity can be calculated, which is shown in Fig. 3.

As shown in Fig. 3, moisture affects $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ curves in all frequency regions. The value of $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ increases gradually with the increase of mc%. Affected by moisture, the $\varepsilon'(\omega)$ curves change significantly in the low-frequency region ($10^{-4} \sim 10^0$), while the $\varepsilon''(\omega)$ curves change significantly in the middle-frequency and high-frequency region ($10^{-2} \sim 10^2$). Thus, the relationship between mc% and frequency spectroscopy can be established, which is the basis for evaluating moisture content in oil-immersed cellulose insulation by the FDS technique.

**B. THE PLATFORM AND RESULTS OF FDS TEST**

To construct a model, oil-immersed pressboards prepared for Experiment 1 are selected for the dielectric response test. The designed FDS test platform is shown in Fig. 2, including DIRANA, three-electrode test cell, thermostat box, high-temperature-resistant wire, and PC. The distance between the two electrodes is equal to the thickness of the measuring oil-immersed pressboard (i.e., 1.0mm). FDS test was performed at 45°C, with a testing voltage and a frequency region of AC 200V and $2 \times 10^{-4}$Hz-5000Hz.
III. THE THEORY OF THE EXPONENTIAL DECAY MODEL

When an AC electric field is applied, the free charge and bound charge inside the dielectric will establish the conductance response and polarization response. The complex relative permittivity \( \varepsilon^*(\omega) \) is put forward to facilitate the study of dielectric properties under alternating electric fields, and its expression is shown in (1).

\[
\varepsilon^*(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega)
\]

In view of the contribution of polarization and the conductance, the mathematical expression of \( \varepsilon'(\omega) \) and \( \varepsilon''(\omega) \) can be written as (2).

\[
\begin{align*}
\varepsilon'(\omega) &= \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + (\omega \tau)^2} + \frac{\sigma_{dc}}{\varepsilon_0 \omega} \\
\varepsilon''(\omega) &= (\varepsilon_S - \varepsilon_\infty) \cdot \frac{\omega \tau}{1 + (\omega \tau)^2} + \frac{\varepsilon_0 \omega}{\varepsilon_0 \omega}
\end{align*}
\]

where \( \varepsilon_0, \varepsilon_\infty, \) and \( \varepsilon_S \) are the vacuum permittivity, the optical permittivity and the static permittivity respectively. \( \sigma_{dc} \) is DC conductivity. \( \varepsilon''(\omega) \) corresponds to the loss term and \( \varepsilon'(\omega) \) corresponds to the energy storage term.

Although Fig. 3 shows that moisture affects both \( \varepsilon'(\omega) \) curve and \( \varepsilon''(\omega) \) curve, it can be seen from (2) that compared to \( \varepsilon''(\omega) \) containing conductance information and polarization information, \( \varepsilon'(\omega) \) only characterize polarization information, which is easier to analyze. Besides, moisture only slightly affects the shape of \( \varepsilon'(\omega) \) curve, which makes it possible to use a unified model to simulate \( \varepsilon'(\omega) \) curve and analyze the internal mechanism. Therefore, the \( \varepsilon'(\omega) \) is more suitable for studying the influence of moisture on polarization, and the \( \varepsilon'(\omega) \) is selected as the research object of this work.

Dielectric response is the superposition of different relaxation processes [32]. In other words, the \( \varepsilon'(\omega) \) reveals the total polarization response intensity, which is the superposition of various sub-polarization intensity. The intensity of each sub-polarization changes with the frequency. Thus, the obtained \( \varepsilon'(\omega) \) is equal to the sum of the corresponding intensity of the sub-polarization response during the FDS measurement. If functional formula \( k_n \cdot \varepsilon'_n(\omega) \) \( (k_n \) is the function factor, \( n = 0, 1, 2, \ldots) \) is used to express the intensity of the sub-polarization response mentioned above. In an effective frequency interval \( f_j \varepsilon(f_j, f_b) \), the superposition of response intensity is expressed by (3).

\[
\varepsilon'(\omega) = k_0 \varepsilon_0'(\omega) + k_1 \varepsilon_1'(\omega) + \cdots + k_n \varepsilon_n'(\omega)
\]

The superposition activity of the \( \varepsilon'(\omega) \) of the cellulose insulation material is shown in Fig. 4. The obtained discretely point of \( \varepsilon'(\omega) \) in the effective frequency interval can be described by the finite exponential decay function.

The dielectric response function decreases exponentially with increasing frequency, which is the so-called frequency-dependence [33]. Therefore, \( k_n \cdot \varepsilon'_n(\omega) \) in (3) can be expressed by a series of exponential decay functions whose independent variable is frequency, which is shown in (4).

\[
\begin{align*}
\varepsilon'(\omega) &= \Psi_0 + \Psi_1 \cdot e^{-(\omega - \omega_0)/\mu_1} + \Psi_2 \cdot e^{-(\omega - \omega_0)/\mu_2} + \cdots + \Psi_n \cdot e^{-(\omega - \omega_0)/\mu_n} \\
\varepsilon'(\omega) &= \Psi_0 + \sum_{i=1}^{n} \varepsilon_i \cdot e^{-(\omega - \omega_0)/\mu_i}
\end{align*}
\]

Then, (3) can be further written as (5), and the combination of a series of exponential functions in the equation is called the "exponential decay model".

\[
\varepsilon'(\omega) = \Psi_0 + \psi_1 \cdot e^{-(\omega - \omega_0)/\mu_1} + \psi_2 \cdot e^{-(\omega - \omega_0)/\mu_2} + \cdots + \psi_n \cdot e^{-(\omega - \omega_0)/\mu_n} \quad (5)
\]

where, \( n \) is the number of sub-polarization responses \( (n = 0, 1, \ldots) \). \( \omega \) is the angular frequency and equal to \( 2\pi f \). \( \Psi_0 \) is the intercept of the exponential function. \( \psi_i \) is the coefficient of each sub-response function. \( \mu_i \) is the decay coefficient. When testing FDS, the initial frequency can be set to a very small value (i.e., \( \omega_0 \rightarrow 0 \)), which is expressed in (6).

\[
\varepsilon'(f) = \Psi_0 + \sum_{i=1}^{n} \psi_i \cdot e^{-2\pi f / \mu_i}
\]

Compared with the linear rectangular coordinate system, the logarithmic coordinate system is more effective in characterizing the variation law of dielectric response. Thus, variables of (6) are presented logarithmically in (7).

\[
\begin{align*}
\log[\varepsilon'(f)] &= \Psi_0 + \sum_{i=1}^{n} \psi_i \cdot e^{\log(f) / \mu_i} \\
\Rightarrow \varepsilon'(f) &= 10^\left[\Psi_0 + \sum_{i=1}^{n} \psi_i \cdot \log(f) / \mu_i\right]
\end{align*}
\]

As analyzed above, the \( \varepsilon'(\omega) \) of the oil-immersed cellulose insulation is equal to the superposition of each sub-polarization intensity, which is related to the frequency.
However, the intensity of the dielectric response will change with the invasion of moisture. In other words, as a strong polar molecule, the water molecule could affect the intensity of internal response. Thus, the exponential decay model used to simulate dielectric response should consider the moisture. In this case, Parameters ($\Psi_i$ and $\mu_i$) in the exponential decay model are related to moisture content, which is shown in (8).

$$\varepsilon'(f, mc\%) = 10 \left[ \Psi_0(mc\%) + \sum_{i=1}^{n} \Psi_i(mc\%) \cdot e^{-\frac{\mu_i}{\mu_i}} \right]$$

(8)

### IV. SIMULATION OF THE FDS CURVE AND CONSTRUCTION OF FDS CURVE DATABASE

#### A. ANALYSIS AND SIMULATION OF FDS CURVES BASED ON THE EXPONENTIAL DECAY MODEL

As mentioned in section III, the $\varepsilon'(\omega)$ curve can be used to analyze the internal polarization information of the cellulose insulation material and the moisture content can be evaluated by studying the intensity of the polarization response. In a limited interval of the frequency, the exponential decay model can simulate the change law of the polarization response intensity. The feature parameters ($\Psi_i$ and $\mu_i$) used in the exponential decay model are affected by the moisture, and they could determine the shape of the simulated curve by model. Therefore, by simulating the $\varepsilon'(\omega)$ curve, a relationship between the $mc\%$ and parameters extracted from the exponential decay model can be established. Based on (8), fitting each group of measurement values in Fig. 3(a), and the fitting curve of $\varepsilon'(\omega)$ is obtained and shown in Fig. 5.

Fig. 5 shows the measured value of $\varepsilon'(\omega)$ and the corresponding simulating curves with different model orders (i.e., $n = 2, 3, 4$). The goodness of fitting for various model orders is illustrated in Table 3.

**TABLE 3.** The comparison of average of goodness of fitting with different model orders.

| Model order ($n$) | $n=2$ | $n=3$ | $n=4$ |
|------------------|-------|-------|-------|
| Average $R^2$    | 0.981 | 0.991 | 0.996 |}

Theoretically, the value of model orders determines the fitting goodness, specifically, the higher the order, the better the fitting goodness. This is also demonstrated by the results shown in Fig. 5 and Table 3. When $n = 3$, the average $R^2$ between the measured values and simulating curves is above 0.99, and the fitting accuracy is satisfactory. Although the fitting goodness when $n = 4$ is better, the probability measure tends to be over-fitting. In addition, if the order is higher, the constructed model will be more complicated. Therefore, the model order $n = 3$ is selected to simulate $\varepsilon'(\omega)$ curves and extract relevant parameters. Table 4 depicts the parameters ($\Psi_i$ and $\mu_i$) of the simulating curves and the goodness of fitting ($R^2$) obtained from (8) ($n = 3$).

It can be seen from Fig. 5 that as the frequency increases, $\varepsilon'(\omega)$ decreases exponentially and finally becomes flat.

**TABLE 4.** The values of the parameters contained in the simulating curves ($n=3$).

| Parameters  | Moisture content (%) |
|-------------|----------------------|
| $\Psi_0$    | 0.91%                |
| $\Psi_1$    | 1.31%                |
| $\Psi_2$    | 1.81%                |
| $\Psi_3$    | 2.47%                |
| $\mu_1$     | 3.24%                |
| $\mu_2$     | 3.84%                |
| $\mu_3$     | 3.95%                |
| $R^2$       | 0.9919               |
|             | 0.9857               |
|             | 0.9888               |
|             | 0.9863               |
|             | 0.9961               |
|             | 0.9980               |}

The exponential decay model simulates the changes well. When the frequency close to 0, the static permittivity reaches its maximum value. The intensity of interface polarization
and dipole polarization decreases with the increase of frequency. When frequency increases to a certain value, the polarization response cannot maintain under the changing AC electric field, and the polarization process cannot be established. In this case, $\varepsilon'(\omega)$ remains unchanged in the high-frequency region. Moreover, the increase of water molecules not only greatly strengthens the intensity of interface polarization dominated in the low-frequency region, but also promotes the dipole polarization phenomenon in the high-frequency region to a certain extent. But the intensity of dipole polarization is much smaller than the interface polarization.

Therefore, the effect of moisture on the low-frequency region is significant, but insignificant in the high-frequency region. The interesting phenomenon is that the moisture will not change the exponential trend of the curve with frequency, which makes it possible to establish the functional relationship between $mc\%$ and parameters extracted from the exponential decay model.

From Table 4, the parameters ($\Psi_i$ and $\mu_i$) change regularly with the increasing moisture. Each group of parameters is respectively processed by fitting, then, fitting curves are obtained and shown in Fig. 6. Table 5 presents the fitting equations for each parameter, which provides a reliable basis

**TABLE 5. The fitting equation for parameters.**

| Parameters | Equation                                                                 | $R^2$  | RCS      |
|------------|--------------------------------------------------------------------------|--------|----------|
| $\Psi_0$  | $\Psi_0 = -0.237 \cdot \text{EXP}(-mc\% / 3.427) + 2.219$                | 0.998  | 5.23E-6  |
| $\Psi_1$  | $\Psi_1 = -0.595 \cdot \text{EXP}(-mc\% / 1.214) + 0.668$               | 0.970  | 5.14E-4  |
| $\Psi_2$  | $\Psi_2 = -0.737 \cdot \text{EXP}(-mc\% / 5.796) + 0.971$               | 0.991  | 1.33E-4  |
| $\Psi_3$  | $\Psi_3 = -0.991 \cdot \text{EXP}(-mc\% / 0.792) + 0.356$               | 0.980  | 4.79E-4  |
| $\mu_1$   | $\mu_1 = -0.003 \cdot \text{EXP} \left[ -2 \cdot \frac{mc\% - 1.922}{2.944} \right] + 0.003$ | 0.972  | 2.63E-6  |
| $\mu_2$   | $\mu_2 = 4.09E-4 \cdot \text{EXP}(mc\% / 0.776) + 7.82E-4$              | 0.997  | 2.33E-6  |
| $\mu_3$   | $\mu_3 = \frac{-1.111}{1 + \text{EXP}(mc\% / 2.486 / 0.131)} + 1.265$   | 0.997  | 1.98E-3  |

*Note: $R^2$ represents the determination coefficient; RCS represents the sum of squared residuals. If the values of RCS and $R^2$ are close to 0 and 1, respectively, the fitting will be better.
for quantitatively describing the law between moisture and parameters (Ψᵢ and µᵢ), and ε′(ω) simulated curves under any mc% can further be predicted.

**B. CONSTRUCTION OF THE FDS CURVE DATABASE**

From the fitting equations in Table 5, the parameters (Ψᵢ and µᵢ) under any mc% can be calculated. Then, using the exponential decay model (i.e., (8)), a series of ε′(ω) simulated curves within sampling frequency is predicted. Therefore, the so-called “FDS curve database” was established by combining these curves, and this database could be used to evaluate the moisture content of oil-immersed pressboards.

In order to construct the FDS curve database, a parameter set of the exponential decay model is established to simulate ε′(ω) curves under different mc%, which are listed in matrix form in (9), as shown at the bottom of the page. By using all equations shown in Table 5, the parameters (Ψᵢ and µᵢ) in the matrix can be calculated when substituting the given moisture. Four equations in Table 5 express the relationship between Ψᵢ (i = 0, 1, 2, 3) and mc%, and other equations express the relationship between µᵢ (i = 1, 2, 3) and mc%.

The moisture content could be calculated by (10). N is the number of the ε′(ω) simulated curves and belongs to the natural number, ranging from 0 to 22. Representing the accuracy of the moisture value, the altering step is set to 0.2%. Transformers are dried during the manufacturing process until moisture content in the cellulosic insulation is less than 0.5%—1.0% [34]. In an actual situation, aging by-products may increase paper moisture. Considering the influence of aging by-products, the minimum value of mc% is set to 0.7%.

In order to more expanded regions to develop the model, mc%=5.1% (when N = 22) is set as a maximum value of moisture content predicted by the database, then, 23 results of moisture content can be obtained by (10).

\[
mc\% = 0.7\% + 0.2\% \cdot N \quad (10)
\]

Combining (9), parameters of ε′(ω) simulated curve under corresponding mc% can be obtained. According to (8), 23 simulating curves are predicted by the exponential decay model in the sampling frequency range, which is displayed in the three-dimensional system with “f-mc%-ε′(ω)” as the coordinate axis (Fig. 7(a)). If the altering step is smaller, more curves will be predicted within the same interval of frequency and moisture content. In other words, as long as the accuracy is small enough, the predicted curves will form a continuous and smooth surface within the same interval of frequency and moisture content (Fig. 7(b)). This surface is considered as a larger FDS curve database, which can characterize more moisture states.

\[
\begin{bmatrix}
ε'_1(f, mc_1\%) \\
ε'_2(f, mc_2\%) \\
ε'_3(f, mc_3\%) \\
\vdots \\
ε'_m(f, mc_m\%)
\end{bmatrix} =
\begin{bmatrix}
Ψ_{10}(mc_1\%) & Ψ_{11}(mc_1\%) & Ψ_{12}(mc_1\%) & Ψ_{13}(mc_1\%) & μ_{11}(mc_1\%) & μ_{12}(mc_1\%) & μ_{13}(mc_1\%) \\
Ψ_{20}(mc_2\%) & Ψ_{21}(mc_2\%) & Ψ_{22}(mc_2\%) & Ψ_{23}(mc_2\%) & μ_{21}(mc_2\%) & μ_{22}(mc_2\%) & μ_{23}(mc_2\%) \\
Ψ_{30}(mc_3\%) & Ψ_{31}(mc_3\%) & Ψ_{32}(mc_3\%) & Ψ_{33}(mc_3\%) & μ_{31}(mc_3\%) & μ_{32}(mc_3\%) & μ_{33}(mc_3\%) \\
\vdots \\
Ψ_{m0}(mc_m\%) & Ψ_{m1}(mc_m\%) & Ψ_{m2}(mc_m\%) & Ψ_{m3}(mc_m\%) & μ_{m1}(mc_m\%) & μ_{m2}(mc_m\%) & μ_{m3}(mc_m\%)
\end{bmatrix}
\] (9)
In order to evaluate the moisture by using the established database, the Euclidean closeness [35] is introduced. It is the most commonly used method to analyze the difference between the tested curve and the \( \varepsilon'(\omega) \) simulated curves in the database, which is shown in (11).

\[
N(\varepsilon'_A, \varepsilon'_B) = 1 - \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\varepsilon'(\omega_i)_A - \varepsilon'(\omega_i)_B)^2}
\]  

(11)

where, \( \omega_i \) is the frequency of the tested point, which ranges from 0.0002~5000Hz; \( n \) is the number of test points, and \( n = 24 \). \( \varepsilon'_A \) and \( \varepsilon'_B \) represent the \( \varepsilon'(\omega) \) curve of the test sample and the \( \varepsilon'(\omega) \) simulated curve in the database, respectively. \( N(\varepsilon'_A, \varepsilon'_B) \) is the closeness degree of A and B, and the larger the value of \( N(\varepsilon'_A, \varepsilon'_B) \), the closer the two curves are.

The closeness degree between the tested curve and the \( \varepsilon'(\omega) \) simulated curves in the database under each \( mc\% \) are calculated, which is shown in Fig. 10. According to the principle of “selecting near” [35], the maximum closeness degree is selected, and the moisture state of the tested sample can be obtained.

From Fig. 10, for each pressboard, a larger value of closeness degree means that its corresponding \( mc\% \) is closer to the evaluation result. Besides, it reveals that if \( mc\% \) of samples is closer, the similarity of their corresponding curve will be higher. This result is consistent with the influence law of moisture on the FDS.

Although the evaluation results based on the principle of “selecting near” are satisfactory, quantitative error analysis on the evaluation results is still necessary to prove the reliability. Equation (12) is used to calculate the relative error (RE) between the evaluation value and the measurement value of the \( mc\% \) of the oil-immersed pressboard. It is worth mentioning that the measurement value of \( mc\% \) is KFT measured results. The evaluation results, measurement value and RE are listed in Table 6. The relative error is within 10.57%, which is acceptable. Thus, the feasibility and accuracy of this method for evaluating the moisture content of oil-immersed pressboards are verified.

\[
RE = \left| \frac{\text{Measured } mc\% - \text{Evaluated } mc\%}{\text{Measured } mc\%} \right| \times 100\%
\]  

(12)
Although the feasibility and accuracy of the proposed method has been preliminarily verified by three samples, the model can be further optimized if samples and obtained data are sufficient, the verification results can be more detailed and forceful.

The temperature has a significant effect on the dielectric response of oil-paper insulation. Thus, if the influence of temperature on the FDS curve is ignored, the evaluation result is not reliable. From the previous discussion, the reported database and the FDS curve database are established at temperature 45°C. In fact, the FDS curves of the test sample at any temperature can be corrected by using the “master curve” technique [22], [23], then the moisture can be evaluated by using the reported database.

VI. CONCLUSION

The previous methods of moisture evaluation rely on limited samples, which restrains the accuracy of evaluation. In view of this issue, a novel and more accessible method for evaluating moisture of oil-immersed cellulose insulation is proposed, among which the FDS curve database is established with the help of the exponential decay model. The present findings and analysis have led to the following conclusions:

i. The polarization response intensity of the oil-immersed insulation pressboard reflects the accumulation of various sub-polarization intensities. The exponential decay model is established to simulate the polarization response intensity.

ii. The parameters (Ψ and μ) defined in the exponential decay model could determine the shape of the simulated curve, which is sensitive to the moisture content. The quantitative relationship between parameters (Ψ and μ) and mc% is established by analyzing and fitting the FDS data.

iii. According to the obtained relationship between parameters and moisture, the ε′(ω) simulated curves corresponding to different mc% can be predicted by the exponential decay model. Then, the FDS curve database can be obtained by using these simulated curves to enable moisture evaluation.

iv. The feasibility and accuracy of the FDS curve database are verified by experiments (relative errors within 10.57%). It is proved that the exponential attenuation model could be used to simulate the FDS curve, and the constructed FDS curve database can be used for the preliminary evaluation of the moisture content of the oil-immersed cellulose insulation.

For further study, the proposed model still needs to be optimized. In this paper, the parameters, fitting equations and constructed models are largely dependent on the characteristics of testing samples, such as the size of samples, degree of aging, etc. Therefore, to achieve a wide application of this model under various conditions, more factors other than moisture (e.g., dimensional parameters and aging parameters) need to be considered.

REFERENCES

[1] J. Liu, X. Fan, Y. Zhang, C. Zhang, and Z. Wang, “Aging evaluation and moisture prediction of oil-immersed cellulose insulation in field transformer using frequency domain spectroscopy and aging kinetics model,” *Cellulose*, vol. 27, no. 12, pp. 7175–7189, Aug. 2020.

[2] D. Wang, L. Zhou, X. Li, Y. Cui, H. Li, A. Wang, and W. Liao, “Effects of thermal aging on moisture equilibrium in oil-paper insulation,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 6, pp. 2340–2348, Dec. 2018.

[3] Y. Xie and J. Ruan, “Parameters identification and application of equivalent circuit at low frequency of oil-paper insulation in transformer,” *IEEE Access*, vol. 8, pp. 86651–86658, May 2020.

[4] Y. Cui, H. Ma, T. Saha, C. Ekanayake, and D. Martin, “Moisture-dependent thermal modelling of power transformer,” *IEEE Trans. Power Del.*, vol. 31, no. 5, pp. 2140–2150, Oct. 2016.

[5] L. J. Zhou, G. N. Wu, and J. Liu, “Modeling of transient moisture equilibrium in oil-paper insulation,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 3, pp. 872–878, Jun. 2008.

[6] D. F. Garcia, B. Garcia, and I. C. Burgos, “A review of moisture diffusion coefficients in transformer solid insulation—Part 1: Coefficients for paper and pressboard,” *IEEE Elect. Insul. Mag.*, vol. 29, no. 1, pp. 46–54, Jan. 2013.

[7] M. Bagheri, B. T. Phung, and T. Blackburn, “Influence of temperature and moisture content on frequency response analysis of transformer winding,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 3, pp. 1393–1404, Jun. 2014.

[8] T. Oomen, “Moisture equilibrium charts for transformer insulation drying practice,” *IEEE Trans. Power App. Syst.*, vol. PAS-103, no. 10, pp. 3062–3067, Oct. 1984.

[9] D. Martin and T. Saha, “A review of the techniques used by utilities to measure the water content of transformer insulation paper,” *IEEE Elect. Insul. Mag.*, vol. 33, no. 3, pp. 8–16, May 2017.

[10] D. Martin, T. Saha, T. Gray, and K. Wyper, “Determining water in transformer paper insulation: Effect of measuring oil water activity at two different locations,” *IEEE Elect. Insul. Mag.*, vol. 31, no. 3, pp. 18–25, May 2015.

[11] D. Martin, N. Lelekaakis, C. Ekanayake, T. Saha, and H. Ma, “Improving measurement techniques of power transformer insulation: A study of the intermolecular interactions between water and vegetable oil based dielectrics,” in *Proc. Ann. Rep. Conf. Elect. Insul. Dielectr. Phenomena*, Chengdu, China, Oct. 2013, pp. 1105–1108.

[12] M. A. Ansari, D. Martin, and T. K. Saha, “Investigation of distributed moisture and temperature measurements in transformers using fiber optic sensors,” *IEEE Trans. Power Del.*, vol. 34, no. 4, pp. 1776–1784, Aug. 2019.

[13] W. A. Fessler, T. O. Rouse, W. J. McNutt, and O. R. Compton, “A refined mathematical model for prediction of bubble evolution in transformers,” *IEEE Trans. Power Del.*, vol. 4, no. 1, pp. 391–404, Jan. 1989.

[14] T. K. Saha and P. Purkait, “Investigations of temperature effects on the dielectric response measurements of transformer oil-paper insulation system,” *IEEE Trans. Power Del.*, vol. 23, no. 1, pp. 252–260, Jan. 2008.

[15] S. Sarkar, T. Sharma, A. Baral, B. Chatterjee, D. Dey, and S. Chakravorti, “A new approach for determination of moisture in paper insulation of insitu power transformers by combining polarization-depolarization current and return voltage measurement results,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 6, pp. 2325–2334, Dec. 2013.

[16] H. C. Verma, A. Baral, A. K. Pradhan, and S. Chakravorti, “A method to estimate activation energy of power transformer insulation using time domain spectroscopy data,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 5, pp. 3245–3253, Oct. 2017.

[17] J. F. Liu, X. Fan, Y. Zhang, and S. Li, “Frequency domain spectroscopy prediction of transformer oil-immersed cellulose insulation under diverse temperature and moisture,” *IEEE Trans. Dielectr. Electr. Insul.*, to be published, doi: 10.1109/TDEE.2020.000813.2020.

![Table 6: Evaluation results of samples and relative errors.](image-url)
L. Yang, P. Peng, J. Gao, and X. Liu, “Moisture diagnosis of transformer oil-immersed insulation with intelligent technique and frequency-domain spectroscopy,” IEEE Trans. Ind. Informat., early access, Aug. 4, 2020, doi: 10.1109/TII.2020.3014224.

G. Xia, G. Wu, B. Gao, H. Yin, and F. Yang, “A new method for evaluating moisture content and aging degree of transformer oil-paper insulation based on frequency domain spectroscopy,” Energies, vol. 10, no. 8, p. 1195, Aug. 2017.

J. Liu, X. Fan, Y. Zhang, H. Zheng, and J. Jiao, “Temperature correction to dielectric modulus and activation energy prediction of oil-immersed cellulose insulation,” IEEE Trans. Dielectr. Electr. Insul., vol. 27, no. 3, pp. 956–963, Jun. 2020.

J. Gao, L. Yang, Y. Wang, C. Qi, J. Hao, and J. Liu, “Quantitative evaluation of ageing condition of oil-paper insulation using frequency domain characteristic extracted from modified cole–cole model,” IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 5, pp. 2694–2702, Oct. 2015.

J. Gao, Y. Du, L. Yang, X. Liu, Y. Wang, and R. Yao, “Effect of moisture and thermal degradation on the activation energy of oil–paper insulation in frequency domain spectroscopy measurement,” IET Gener. Transmiss. Distrib., vol. 10, no. 9, pp. 2042–2049, Jun. 2016.

R. Liao, J. Liu, L. Yang, K. Wang, J. Hao, Z. Ma, J. Gao, and Y. Lv, “Quantitative analysis of insulation condition of oil-paper insulation based on frequency domain spectroscopy,” IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 1, pp. 322–334, Feb. 2015.

M. Koch and T. Prevost, “Analysis of dielectric response measurements for condition assessment of oil-paper transformer insulation,” IEEE Trans. Dielectr. Electr. Insul., vol. 19, no. 6, pp. 1908–1915, Dec. 2012.

C. Ekanayake, S. M. Gubanski, A. Graczkowski, and K. Walczak, “Frequency response of oil impregnated pressboard and paper samples for estimating moisture in transformer insulation,” IEEE Trans. Power Del., vol. 22, no. 3, pp. 1309–1317, Jul. 2006.

J. Liu, X. Fan, Y. Zhang, H. Zheng, and M. Zhu, “Quantitative evaluation for moisture content of cellulose insulation material in paper/oil system based on frequency dielectric modulus technique,” Cellulose, vol. 27, no. 4, pp. 2343–2356, Mar. 2020.

S. K. Ojha, P. Purkait, B. Chatterjee, and S. Chakravorti, “Application of cole–cole model to transformer oil-paper insulation considering distributed dielectric relaxation,” High Voltage, vol. 4, no. 1, pp. 72–79, Mar. 2019.

S. Morsalin and B. T. Phung, “Modeling of dielectric dissipation factor measurement for XLPE cable based on davidson-cole model,” IEEE Trans. Dielectr. Electr. Insul., vol. 26, no. 3, pp. 1018–1026, Jun. 2019.

J. Liu, H. Zheng, Y. Zhang, H. Wei, and R. Liao, “Grey relational analysis for insulation condition assessment of power transformers based upon conventional dielectric response measurement,” Energies, vol. 10, no. 10, p. 1526, Oct. 2017.

J. Liu, X. Fan, Y. Zhang, H. Zheng, and C. Zhang, “Condition prediction for oil-immersed cellulose insulation in field transformer using fitting fingerprint database,” IEEE Trans. Dielectr. Electr. Insul., vol. 27, no. 1, pp. 279–287, Feb. 2020.

J. Gao, L. Yang, Y. Wang, X. Liu, Y. Lv, and H. Zheng, “Condition diagnosis of transformer oil-paper insulation using dielectric response fingerprint characteristics,” IEEE Trans. Dielectr. Electr. Insul., vol. 23, no. 2, pp. 1207–1218, Apr. 2016.

M. Dong, M. Ren, F. Wen, C. Zhang, J. Liu, C. Sumereder, and M. Muhr, “Explanation and analysis of oil-paper insulation based on frequency-domain dielectric spectroscopy,” IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 5, pp. 2684–2693, Oct. 2015.

A. K. Jonscher, “Dielectric relaxation in solids,” J. Phys. D. Appl. Phys., vol. 32, no. 14, p. R57, 1999.

Mineral Insulating Oils in Electrical Equipment-Supervision and Maintenance Guidance, IEC Standard 60422, 2013.

L. Yang, P. Peng, J. Gao, and X. Liu, “The range recognition of moisture and aging status of oil-paper insulation based on frequency domain dielectric response characteristic fingerprint,” Trans. China Electrotech. Soc., vol. 33, no. 9, pp. 2105–2114, Nov. 2018.

JIEFENG LIU (Member, IEEE) was born in Hebei, China, in 1985. He received the M.S. and Ph.D. degrees in electrical engineering from Chongqing University, Chongqing, China, in 2011 and 2015, respectively. He is the author and coauthor of over 40 articles published in journals and conferences. His research interests include the field of condition assessment and insulation fault diagnosis for oil-paper insulation on high voltage apparatus.

ZIXIAO WANG was born in Hubei, China, in 1996. She received the bachelor’s degree in electrical engineering from the Heilongjiang University of Science and Technology, Harbin, China, in 2018. She is currently pursuing the M.S. degree with Guangxi University, Nanning, China. Her current research interests include condition assessment and insulation fault diagnosis for oil-immersed insulation on high voltage apparatus.

XIANHAI FAN (Student Member, IEEE) was born in Gansu, China, in 1995. He received the bachelor’s degree in electrical engineering from Guangxi University, Nanning, China, in 2018, where he is currently pursuing the Ph.D. degree. He is the author and coauthor of over ten articles published in SCI journals. His current research interests include condition assessment and insulation fault diagnosis for oil-paper insulation.

YIYI ZHANG (Member, IEEE) was born in Guangxi, China, in 1986. He received the bachelor’s degree in electrical engineering from Guangxi University, Nanning, China, in 2008, and the Ph.D. degree in electrical engineering from Chongqing University, Chongqing, China, in 2014. In 2014, he joined Guangxi University, where he is currently an Associate Professor with the College of Electrical Engineering. He is the author and coauthor of over 40 articles published in SCI journals. His current research interest includes the intelligent diagnosis for transformers.

JIAQI WANG was born in Guangxi, China, in 1996. She received the bachelor’s degree in electrical engineering from Guangxi University, Nanning, China, in 2018, where she is currently pursuing the master’s degree in electrical engineering. Her current research interests include fault diagnosis of electrical equipment and energy-environment-economy nexus analysis.