A Circuital Model-Based Analysis of Moisture Content in Oil-Impregnated-Paper Insulation Using Frequency Domain Spectroscopy

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This work was supported in part by the Fundamental Research Funds for Central Universities under Grant SWU119042.

ABSTRACT The explicitly numerical or well-defined correlations between the dielectrics responses (DRs) and dielectric essences of oil-impregnated paper (OIP) insulation have not been fully understood yet. As a result, it is rather difficult to quantitatively diagnose the critical insulation condition, like determining moisture content in insulation paper (MCP) of power equipment only using electrical-based techniques such as frequency domain spectroscopy (FDS). To obtain MCP value, from a new perspective of parametric study on the circuital DR equivalence of OIP insulation—extended Debye model (EDM), the present contribution introduces a novel approach by exploring the pattern when EDM parameters vary with MCP and temperatures \( T \). Further, mathematical correlations are developed between sensitive \( R-C \) values and MCP-\( T \) values. On the above analysis, small-scale physical models of real-life transformer bushings were prepared as test samples. Their OIP condenser bodies were artificially absorbed different controlled quantities of moisture and conditioned at different temperatures to record corresponding FDS results. Then a hybrid genetic algorithm combined with the Levenberg-Marquardt algorithm was proposed to estimate the EDM parameters by fitting the measured FDS data. Sensitive parameters therein were identified using sub-spectrum decomposition and formulated with MCP-\( T \) values so that a reliable moisture content estimation can be achieved once the testing temperature and FDS recordings of an insulation body are known.

INDEX TERMS Oil-impregnated-paper insulation, moisture, extended Debye model, frequency domain spectroscopy.

I. INTRODUCTION

Three sources cause water contamination in the oil-impregnated paper (OIP) insulation: residual moisture after manufacture, ingress from the atmosphere, and aging of cellulose and oil [1], [2]. Due to the hygroscopic nature of paper, most of the moisture resides in the paper rather than in the insulation oil [3]. On the other hand, the dryness state of oil-impregnated paper (OIP) insulation significantly concerns the operational reliability of OIP insulated appliances in a power system, such as power transformers and bushings. The presence of moisture in cellulose causes three detrimental effects: it decreases the dielectric withstand strength, raises the emission of water vapor bubbles, and accelerates cellulose aging [4], [5]. The equipment may fail ultimately due to premature breakdown when insulation reaches the end of its working life sooner as the insulation ages faster accompanied by water [4], [6]. Dampness has become the top threat among all the hazardous factors for insulation health. Therefore, the water content must be monitored at any stage once the equipment is energized. Accurate tracking cellulosic moisture also enables operators to arrange for the refurbishment of the damped equipment using techniques such as on-line oil regeneration, hot-oil hydronic drying and holistic dismantled windings drying in an oasthouse [1].

The moisture content of paper (MCP) is the ratio of the mass of adsorbed water to the mass of dry paper, usually expressed as a percentage [7]. Various techniques have been proposed to determine MCP for utilities to implement routine tests or laboratory studies. The most direct method is...
Karl Fischer titration (KFT) [6], [8]. Karl Fischer titration is a method in analytical chemistry that traces amounts of water in a sample using volumetric or coulometric titration. The constraint of the KFT method is that collecting the paper sample for the test from objective equipment is nearly impossible unless the equipment is scrapped and overhauled. Unlike insulation paper, insulating oil can be practically extracted and the moisture content in oil (MCO) can also be measured by KFT or oil humidity probe [9]. Therefore, an alternative to estimate MCP is to back-calculate it from MCO based on adsorption isotherms[10]. However, sampling the oil is susceptible to ambient moisture, which leads to MCO error. Besides, the MCO and MCP equilibrium cannot be reached within any real-life OIP insulated equipment as the operational and environmental condition is changing continually.

In recent years, dielectric response (DR) methods have become one of the most effective electrical approaches to estimate the insulation condition of power equipment. The DR-based method is a family of nondestructive measurement applied on OIP insulation, which includes two time-domain and one frequency-domain DRs measurements—recovery voltage method (RVM), polarization/depolarization current (PDC) and frequency domain spectroscopy (FDS) [7], [11]. Therein, FDS measurement is considered to be the most important and promising method to diagnose the OIP insulation condition due to its anti-interference feature and wide-band DR information. To achieve a reliable assessment from FDS, an underlying and critical problem when using FDS measurements is the interpretation of FDS results towards insulation condition changes, which should be clearly understood. At present, the approaches for FDS interpretation includes: evaluating the moisture status of OIP insulation qualitatively by observing and comparing test FDS trances with that of reference sample [12]; identifying the characteristic parameters from the FDS curves and formulating numerical correlations with the conventional condition status indicators like MCP or degree of polymerization (DP) [13], [14]. Except for the above two methods that depend on seeking “direct” evidence, another approach which intends to give criterion of insulation condition from more “physical” perspective is to establish and parameterize dielectric equivalent models based on FDS data, and the characteristic quantities can be recognized thereby by analyzing the model parameters [15], [16], which can effectively signify the information of insulation state in the wide-band frequency range indicated by FDS curve.

As model-based features can provide both numerical judgments as well as physical explanations, a considerable body of literature dedicates on the attempt of finding characteristic quantities of insulation status from different equivalent models for OIP insulation. J. Liu et al. calculated the parameters of EDM using PDC curves by a stepwise fitting method, and quantified the moisture content of insulation pressboard by referencing the slope of polarization charge quantity regarding time and stable polarization charge quantity calculated from depolarization currents [17]; A. Baral et al. obtained the maximum absolute value of the zero points in the transfer function of the equivalent model (EDM), which was found sensitive to moisture and aging changes of OIP insulation [18]. J. Gao et al. found that the polarization resistance in the large-time-constant branch and the polarization capacitance in the small-time-constant branch demonstrate a linear fitting relationship with DP value, which can characterize the aging state of OIP insulation [19]. J. Song et al. pointed out that the aging of transformer oil and insulation paper affects the parameters of the small-time-constant branch and the large-time-constant branch of EDM respectively [20]. The resistance decreases and the capacitance increases with the aging degree increased. J. Cai et al. reported that the furfural amount in the oil is related to the branch parameters of EDM within large-time-constant branch, where there is a linear relationship between the furfural content in the oil and the branch time constant, and that the furfural content is positively and inversely proportional to the branch capacitance and resistance respectively [21].

However, most of the existing explorations on model-based characteristic quantities are limited to seeking the relationship between a single characteristic parameter and traditional insulation state index, which demonstrates problematic and unreliable evaluation results due to the one-sidedness nature of dielectric information carried in any single indicative quantity in terms of actual complex dielectric behaviors in any real insulation system. To this end, by analyzing the equivalent model, the present study discusses the correlation between changes in the model parameters and insulation state. After that, multi characteristic parameters are determined to apply the comprehensive analysis of insulation moisture state. In the remainder of this paper, scale-down models of real oil-impregnated condenser bushings were prepared and a test platform for artificial moisturization of the bushings was built. The FDS of the bushings with different moisture content under controlled temperatures were measured. Then the extended Debye model of OIP insulation in a broad frequency band was established by the GA-LMA optimization algorithm which was applied to the measured FDS results. Based on the calculated model parameters, the variation pattern of the EDM parameters regarding the temperatures and moisture contents was analyzed. The essential relationship between the branch parameters and FDS curves was discussed using the proposed sub-spectrum decomposition analysis. Finally, the characteristic quantities representing insulation moisture state were excavated to for evaluating the moisture level of the OIP insulation.

II. FREQUENCY-DOMAIN SPECTROSCOPY-BASED PARAMETERIZATION OF EXTENDED DEBYE MODEL

A. EXTENDED DEBYE MODEL

A dielectric subjected to an external electric field exhibits two types of dielectric behaviors at the microscopic scale: conduction and polarization. The extended Debye model (EDM) can interpret the two dielectric behaviors
FIGURE 1. Extended Debye model.

Phenomenologically and physically, and therefore, is widely used as an equivalent circuit model to macroscopically simulate the dielectric response of oil-paper insulation systems [22], [23], as shown in Figure 1. In the model, \( C_0 \) is the total equivalent capacitance of the geometric capacitance and lossless polarization, \( R_0 \) is the insulation resistance that indicates the conductivity of the media, and the parallel \( R_i-C_i \) branches are the approximation of the complex relaxation polarization processes in the dielectric, where \( C_i \) is the polarization capacitance which signifies the capacity of the dielectric to accumulate charges and \( R_i \) is polarization resistance that characterizes material generating power loss in a polarization process.

The EDM is in the form of a circuit with capacitors and resistors. From the perspective of circuit theory, EDM can simulate the frequency characteristics of the material (FDS) based on the impedance characteristic of the circuit. FDS that is performed on real dielectric insulation systems obtains their real capacitance, imaginary capacitance, and dielectric dissipation factor in response to frequency variations. On the other hand, under the equivalence of insulation material and the circuit model (Fig. 1), FDS can be calculated using the following two equations once the model parameters are known:

\[
C'(\omega) = \text{Re}\left[\frac{1}{j\omega Z}\right] = C_0 + \sum_{i=1}^{n} \frac{C_i}{1 + (\omega R_i C_i)^2} \tag{1}
\]

\[
C''(\omega) = \text{Im}\left[\frac{1}{j\omega Z}\right] = \frac{1}{\omega R_0} + \sum_{i=1}^{n} \frac{\omega R_i C_i^2}{1 + (\omega R_i C_i)^2} \tag{2}
\]

where \( C'(\omega) \) and \( C''(\omega) \) are the real and imaginary components of the complex capacitance, respectively. Then, the tangent of the dielectric loss angle is defined as the ratio of the imaginary capacitance to the real capacitance:

\[
\tan \delta = \frac{C''(\omega)}{C'(\omega)} \tag{3}
\]

**B. Parameterization of the Extended Debye Model**

In this paper, if the EDM is quantitatively parameterized with respect to actual dielectric response measurements, then it can be employed to quantitatively predict the insulation condition of insulation systems. The essence of the model parameterization is to estimate the capacitances and resistances in each branch of the EDM and then verify the estimates against measurements of the two parameters, which can be solved as a multi-parameter nonlinear optimization problem.

Since the three parameters of interest—the real capacitance, imaginary capacitance, and dielectric dissipation factor—are of pairwise independence, only two of them—real and imaginary capacitance were selected here as reference data for the parameterization.

As the difference between the measurements of \( C''(\omega) \) at lower and higher frequencies can be up to \( 10^2 \) orders of magnitude, the parameterization using a traditional least-squares method for controlling and minimizing the squares of absolute errors can only accurately simulate the dielectric response at higher frequencies, and thus is less favorable to achieve accurate fitting in broadband frequencies. Also, the parameterization must take the reconstruction consistency of both \( C'(\omega) \) and \( C''(\omega) \) into account. On the above considerations, the following function is established for optimizing multiple parameters of the EDM by employing the least-squares weighted relative errors:

\[
\min \sum_{i=1}^{m} \left( \text{weight}(\omega) \left( \frac{(C'_\text{mea}(\omega) - C'_{\text{fit}}(\omega))^2}{C'_\text{mea}(\omega)} + \left( \frac{(C''\text{mea}(\omega) - C''_{\text{fit}}(\omega))^2}{C''\text{mea}(\omega)} \right) \right) \right), \tag{4}
\]

where \( \text{weight}(\omega) \) is a frequency-dependent function of weights that applied on each data point, which is specified by a piecewise function as shown by (5).

\[
\text{weight}(f) = \begin{cases} 
-0.0225 \log_{10}(f)^2 - 0.0315 \log_{10}(f) + 1.0274; & (0.001 < f < 0.01) \\
1; & (0.01 < f < 100) \\
-0.0335 \log_{10}(f)^2 + 0.1177 \log_{10}(f) + 0.89; & (100 < f < 5000)
\end{cases} \tag{5}
\]

As empirical knowledge, FDS in low frequencies is susceptible to moisture changes. On the other hand, the present study aims to reveal moisture status by analyzing the model parameters. Consequently, the contribution of the low-frequency (LF) part of FDS should be more preferentially involved in the parameterization process so that the calculated model parameters can more effectively reflect low-frequency dielectric characteristics on behalf of a clear interpretation of moisture information. On the contrary, LF FDS itself is of low accuracy from the perspective of practical measurement by any FDS testers, which, however, will meanwhile make the resultant model parameters more inaccurate if LF is over weighted. Considering the two aspects, the weighed frequency band should be well balanced. In this paper, full weight is determined to be applied on 0.01-100Hz while the weight at the lower band (<0.01Hz) and higher band (>100 Hz) gradually attenuate. Under the premise of appropriate algorithm-convergence precision, the parameterization of the model essentially finds the optimal solutions for \( R_n \) and \( C_n \) once the optimization Equation (4) approaches zero.
The EDM features a regular circuit structure, however, with varying complexity, which can be determined only if the circuit branch quantity is specified. Therefore, another major premise for the model parameterization is to give the number of polarization branches \( n \) so that the expressions of FDS functions (1) and (2) can be determined. Theoretically, an EDM with more parallel resistor-capacitor (R-C) branches is more veracious in representing the diversification of the relaxation polarization process within a real insulation system. However, an increment of R-C branches leads more parameters to be estimated and therefore result in significant difficulty in solving the nonlinear parameterization. Based on a balanced consideration of the complexity of the model parameterization and the effectiveness of the parameterized model, it was determined that six polarization branches are used for the EDM.

Then, the genetic algorithm (GA) and the Levenberg-Marquardt Algorithm (LMA) were combined in this paper to solve the optimization model (4). The principle of the hybrid algorithm GA-LMA can be briefly described as: first, the GA was used for a global search. After that, the coarse solution obtained by the GA was input into the LMA, which was used for a global search. The flowing chart of the combination of the genetic algorithm (GA) and the Levenberg-Marquardt Algorithm (LMA) is illustrated in Figure 2.

III. DIELECTRIC MEASUREMENTS OF ARTIFICIALLY MOISTURIZED MODEL BUSHINGS

A. THE MODEL BUSING FOR EXPERIMENTS

An OIP condenser bushing is a typical OIP insulated equipment, which is also a critical component of transformers that are used primarily for external connection of high- and low-voltage windings of transformers. As a representative physical instance of OIP insulation, OIP bushings are selected as case studies to provide genuine FDS data sources. The EDM for the bushing was parameterized against measurements obtained from FDS performed on a kind of tailor-made model bushings, which were artificially moisturized with a different controlled quantity of water absorption as test samples.

Real-life transformer bushings are inapplicable for laboratory experiment purposes, as genuine bushings are of operational inconvenience with great volume and weight, and therefore they do not facilitate a quantifiable control of experimental conditions. Alternatively, a kind of downscaled models of transformer bushings was specially designed and prepared for the experiment after this. The models were designed with the most fundamental internal and external insulation structures of real bushings, but have fewer layers of aluminum foils in the condenser body with lower dielectric strengths. Consequently, the resulting models are a reasonable simplification of genuine bushings, but with reduced volumes and weights. Specifically, the models consist of the following critical components: a condenser body, conduction lead, porcelain shell, and flange. Among them, the condenser body is the main insulation inside a bushing, which is subjected to the operating voltage that is applied across the conduction lead and ground. The condenser body of the models was designed with six layers of aluminum foils in a three-step structure. Fig. 3 and Fig. 4 demonstrate schematic illustrations of the model bushing.

B. PREPARATION OF ARTIFICIALLY MOISTURIZED CONDENSER BODIES OF THE MODEL BUSHINGS

The condenser body was pretreated as follows before moisturization. First, the condenser body and the insulating oil were vacuum-dried. The condenser body and the insulating oil were separately placed into two vacuum tanks, as shown in Fig. 5. The loaded tanks were then placed in a temperature chamber with a constant temperature of 90°C. The vacuum tanks in the temperature chamber were periodically vacuum-pumped to ensure the desired degree of vacuum. Both the

\[
R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2},
\]

where \( y_i \) represents the measurements, \( \hat{y}_i \) presents the results predicted by the parameterized model, and \( \bar{y}_i \) is the average of the measurements. The value of \( R^2 \) falls in the range of \((0, 1)\), with a value closer to 1 indicating a higher accuracy of the parameterized model. Since the present study mainly focuses on analyzing the obtained model parameters for seeking their correlations to the insulation condition, the calculation process is only briefly stated as above. More details in this point are available in the previous paper published by the authors [24].

FIGURE 2. The flowing chart of the combination of the genetic algorithm (GA) and the Levenberg-Marquardt Algorithm (LMA).
condenser body and the insulating oil were vacuum-dried for 48 h. The vacuum-dried condenser body was then immersed in the vacuum-dried insulation oil in a vacuum tank at a temperature of 60°C for 48 h, and then the vacuum tank was pumped with nitrogen and the condenser body was immersed in the insulation oil for another 24 h to ensure the condenser body was adequately impregnated with the insulating oil.

The oil-impregnated condenser body was then moisturized by placing it in the air, which was artificially humidified with a humidifier. The condenser body was weighed with a balance periodically to ensure the desired level of moisture content. Three condenser bodies were prepared, with mass fractions of moisture of 0.71%, 1.78%, and 2.62% and numbered model 1, 2, and 3, respectively. The moisturized condenser bodies were then assembled with other components of the bushings. Finally, the assembled bushings were filled with the pre-dried insulating oil. The preparation process of the artificially moisturized bushings is illustrated in Fig.6.

C. DIELECTRIC MEASUREMENT PROCEDURES

A sequence of dielectric-response tests was performed on the prepared bushing samples. The configuration and photographs of the test setup are illustrated in Fig. 7 and Fig. 8. First, the frequency-domain dielectric response of the models was tested using a DIRANA dielectric-response analyzer (Omicron, Germany). The bushings were tested for their dielectric response in the frequency range of 1 mHz to 5 kHz at an output voltage of 200 V under controlled temperatures of 30°C, 40°C, 50°C, 60°C, 70°C, and 80°C using a temperature chamber. Except for FDS measurements, the model bushings were then tested for their insulation resistance using a Keithley 6517B high-resistance meter.

IV. PARAMETERIZATION RESULTS AND ANALYSIS

A. PARAMETERIZATION RESULTS

All parameters of EDM can now be simulated and further determined using already measured characteristics of the model bushing with certain water content and conditioned at different temperatures. A total of 18 groups of above measured FDS curves were applied with the above parameterization to obtain model parameters that are in accordance
with 18 different combinations of OIP status for subsequent analysis.

Fig. 7 to 9 show the measured FDS results—real and imaginary capacitance of the three model bushings (with different moisture content) at six different temperatures (in the range of 30–80°C) and the corresponding FDS calculated by the parameterized EDM. The comparison shows that the FDS predicted by the parameterized EDM fit accurately with the measurements. Table 1–3 list the calculated branch parameters in EDM of the three model bushings. Table 4 lists the goodness of fit for the measurement series, with all $R^2$ values exceeding 0.90, thereby verifying the effectiveness of the parameterized EDM for oil-paper insulation systems. This accurate fitting on all the 18 groups of the measured FDS curves indicates that the parameterized EDM is effective for predicting the frequency domain dielectric response of oil-paper insulation systems in a wide band of frequencies.

### B. INFLUENCE OF TEMPERATURE ON THE EDM PARAMETERS

First, Tables 1 to 3 show that the geometric capacitance $C_0$ varies insignificantly with the temperature. This is because the geometric capacitance is primarily determined by the structure of the insulation body and the instantaneous polarization process, which does not change with temperature. In contrast, the insulation resistance $R_0$ is sensitive to temperature variations and decreases with an increase in temperature. This is because a higher temperature results in more charged ions in the dielectric and faster movements of charged particles. The polarization capacitances $C_i$ with greater time constants are found to increase consistently with temperature, whereas the polarization resistances $R_i$ decrease with temperature. The temperature dependence of $R_0$ and $R_i$ on the activation energy can be explained by the Arrhenius equation [25]. The increment of $C_i$ with temperature would be more pronounced at higher temperatures due to increased mobility of charged particles.

### TABLE 1. The calculated branch parameters in EDM of model bushing no.1.

| Temperature (°C) | 30 | 40 | 50 | 60 | 70 | 80 |
|-----------------|----|----|----|----|----|----|
| $C_{nf}$        | 0.2478 | 0.2487 | 0.2495 | 0.2501 | 0.2506 | 0.2515 |
| $R_{nf}/\Omega$ | 96900 | 44400 | 19400 | 9000 | 4030 | 1800 |
| $C_{nf}$        | 0.0302 | 0.0570 | 0.0982 | 0.1843 | 0.3094 | 0.4714 |
| $R_{nf}/\Omega$ | 32554 | 22627 | 97160 | 49487 | 27783 | 16279 |
| $C_{nf}$        | 0.0256 | 0.0286 | 0.0296 | 0.0336 | 0.0403 | 0.0516 |
| $R_{nf}/\Omega$ | 33436 | 20966 | 12192 | 83854 | 57358 | 35852 |
| $C_{nf}$        | 0.0020 | 0.0022 | 0.0023 | 0.0030 | 0.0041 | 0.0057 |
| $R_{nf}/\Omega$ | 1209.7 | 868.96 | 465.84 | 272.71 | 177.46 | 107.98 |
| $C_{nf}$        | 0.0009 | 0.0009 | 0.0009 | 0.0010 | 0.0009 | 0.0010 |
| $R_{nf}/\Omega$ | 17.671 | 21.807 | 22.968 | 20.083 | 17.667 | 14.302 |
| $C_{nf}$        | 0.0015 | 0.0014 | 0.0013 | 0.0012 | 0.0011 | 0.0010 |
| $R_{nf}/\Omega$ | 0.6764 | 0.7433 | 0.7849 | 0.8253 | 0.8367 | 0.8225 |
| $C_{nf}$        | 0.0024 | 0.0021 | 0.0020 | 0.0019 | 0.0017 | 0.0017 |
| $R_{nf}/\Omega$ | 0.0190 | 0.0219 | 0.0240 | 0.0256 | 0.0265 | 0.0271 |

### TABLE 2. The calculated branch parameters in EDM of model bushing no.2.

| Temperature (°C) | 30 | 40 | 50 | 60 | 70 | 80 |
|-----------------|----|----|----|----|----|----|
| $C_{nf}$        | 0.2449 | 0.2466 | 0.2483 | 0.2495 | 0.2502 | 0.2540 |
| $R_{nf}/\Omega$ | 1440 | 422 | 139 | 49.8 | 18.1 | 7.07 |
| $C_{nf}$        | 0.0995 | 0.0831 | 0.0827 | 0.0906 | 0.0982 | 0.1896 |
| $R_{nf}/\Omega$ | 670.20 | 540.95 | 313.44 | 206.74 | 168.20 | 281.35 |
| $C_{nf}$        | 0.0449 | 0.0741 | 0.0858 | 0.0913 | 0.1068 | 0.0950 |
| $R_{nf}/\Omega$ | 252.23 | 81.316 | 29.762 | 11.628 | 5.2421 | 2.7207 |
| $C_{nf}$        | 0.0578 | 0.0563 | 0.0549 | 0.0543 | 0.0531 | 0.0519 |
| $R_{nf}/\Omega$ | 4.5665 | 2.1461 | 1.0683 | 0.5828 | 0.3941 | 0.2736 |
| $C_{nf}$        | 0.0287 | 0.0287 | 0.0271 | 0.0228 | 0.0191 | 0.0160 |
| $R_{nf}/\Omega$ | 0.4374 | 0.2216 | 0.1358 | 0.1172 | 0.1264 | 0.1467 |
| $C_{nf}$        | 0.0036 | 0.0095 | 0.0121 | 0.0165 | 0.0213 | 0.0256 |
| $R_{nf}/\Omega$ | 0.1361 | 0.0930 | 0.0608 | 0.0589 | 0.0283 | 0.0210 |
| $C_{nf}$        | 0.0034 | 0.0036 | 0.0038 | 0.0041 | 0.0045 | 0.0048 |
| $R_{nf}/\Omega$ | 0.0155 | 0.0145 | 0.0130 | 0.0118 | 0.0107 | 0.0098 |
TABLE 3. The calculated branch parameters in EDM of model bushing no. 3.

| Temperature (°C) | 30   | 40   | 50   | 60   | 70   | 80   |
|------------------|------|------|------|------|------|------|
| C0/R0            | 0.2460 | 0.2482 | 0.2501 | 0.2524 | 0.2556 | 0.2519  |
| R0/G0            | 55   | 19.3 | 7.27  | 4.5   | 1.5   | 1.5   |
| C1/R1            | 0.1436 | 0.2961 | 0.3947 | 0.3966 | 0.4386 | 0.5548  |
| R1/G1            | 431.30 | 200.54 | 79.625 | 36.239 | 30.984 | 3.9707  |
| C1/R1            | 0.0182 | 0.0212 | 0.0239 | 0.0241 | 0.0197 | 0.0477  |
| R1/G1            | 78.341 | 51.980 | 22.738 | 10.538 | 4.5624 | 3.871   |
| C1/R1            | 1.8818 | 0.9237 | 0.4541 | 0.2423 | 0.1783 | 0.0741  |
| R1/G1            | 0.0656 | 0.0637 | 0.0598 | 0.0556 | 0.0551 | 0.0556  |
| C1/R1            | 0.1410 | 0.0838 | 0.0543 | 0.0398 | 0.0336 | 0.0153  |
| C1/R1            | 0.0195 | 0.0227 | 0.0267 | 0.0308 | 0.0282 | 0.0225  |
| C1/R1            | 0.0546 | 0.0350 | 0.0223 | 0.0152 | 0.0146 | 0.0095  |
| C1/R1            | 0.0051 | 0.0057 | 0.0064 | 0.0070 | 0.0067 | 0.0079  |
| R1/G1            | 0.0111 | 0.0097 | 0.0081 | 0.0070 | 0.0069 | 0.0053  |

TABLE 4. The goodness of fit of reconstructed FDS curves.

| Bushing | Temperature (°C) | 30   | 40   | 50   | 60   | 70   | 80   |
|---------|------------------|------|------|------|------|------|------|
| #1      | C  | 0.99  | 0.99  | 0.97  | 0.96  | 0.92  | 0.92  |
|         | C+ | 0.99  | 0.99  | 0.99  | 0.99  | 0.98  | 0.97  |
| #2      | C  | 0.99  | 0.99  | 0.99  | 0.99  | 0.99  | 0.99  |
|         | C+ | 0.99  | 0.99  | 0.99  | 0.99  | 0.99  | 0.99  |
| #3      | C  | 0.99  | 0.99  | 0.99  | 0.99  | 0.98  | 0.94  |
|         | C+ | 0.99  | 0.99  | 0.99  | 0.99  | 0.93  | 0.96  |

is because a higher temperature intensifies polarization of the OIP material and therefore raises a higher susceptibility and permittivity of the complex dielectric, which is linearly correlated with the polarization capacitance $C_i$.

Except for analyzing individual resistance or capacitance in the model, certain time constants of the geometry and polarization branches that are closely related to the relaxation process in the dielectric are found to be sensitive to temperature changes. Fig. 12 shows the variations of the time constants with the temperature of the three model bushings. Therein more consistent trend of the variations with temperature is observed on larger time constants ($t_0 \sim t_3$). These time constants are in a negative correlation with temperature. The largest time constants $t_0$ of the $C_0-R_0$ branch for all the three bushing models decrease significantly with the temperature, which is because a higher temperature leads to faster thermal motions of the dipoles in the oil-paper insulation system. This, in turn, results in a greater reorientation power of the dipoles and a faster relaxation process in the dielectric, thereby resulting in smaller time constants of the polarization branches of the EDM. Judging from the above results, the parameterization is not only in conform to the measured spectrum numerically but can also be physically explainable. The changes in the obtained parameters demonstrate a conspicuous and consistent pattern with temperature.

C. INFLUENCE OF THE MOISTURE CONTENT ON THE EDM PARAMETERS

Similarly, the geometric capacitance $C_0$ demonstrates non-significant changes with the moisture content. This is because the structure and dimension of the oil-paper insulation system are unchanged regarding moisture content, and the instantaneous polarization process is insusceptible of moisture condition. However, the insulation resistance $R_0$ is extremely sensitive to moisture content variations and decreases with an increase in the MCP. This is because moisture introduces highly conductive ions and serves as a catalyst to facilitate faster disintegration of impurities. Therefore, moisture contributes to more charge carriers in the insulation system of the bushing, thereby significantly increasing the conductivity of the system and thus significantly decreasing its insulation resistance. Besides, the polarization capacitances $C_i$ is found to generally increase with the moisture content (except for $C_1$ and $C_2$). In contrast, the polarization resistance $R_i$ decreases with the moisture content.

Fig. 13 shows the variations of the time constants of the EDM branches with the moisture content for the bushing models at the same temperature. The figure demonstrates that the time constant $t_0$ of the $C_0-R_0$ branch significantly decreases with moisture content. Besides, the time constants of the polarization branches decrease with respect to the...
moisture content. This correlation can be explained as follows: water molecules in the electrical field polarize vigorously in the form of dipole reorientation and increase the hydrolysis reaction of cellulose; therefore, the presence of water contributes to an increased number of polarized molecules in the oil-paper system, thereby facilitating the dielectric to bound the charges, which accelerate the relaxation polarization of the system such that the time constants of the polarization branches decrease with the moisture content.

V. CHARACTERISTIC QUANTITIES OF MOISTURE EVALUATION OF OIL-PAPER INSULATION

Frequency-domain spectroscopy is the macroscopic manifestation of the dielectric response in a wide band of frequencies. Variations in the conduction and polarization behavior of a dielectric at the microscopic scale can directly reveal the variations in its frequency domain spectroscopy and therefore influence the parameters of the EDM that simulates the dielectric response. In turn, the parameters of the equivalent model EDM can be quantitatively correlated with the condition of insulation systems. This correlation has been analyzed primarily in the study above. The temperature and moisture content are found to affect the parameters of the equivalent model in a definite and distinct way. After that, attempts have been made here to figure out the analytical correlation between the aforementioned indicative parameter and the corresponding MCP for achieving reliable moisture evaluation.

It is widely accepted that tanδ and the imaginary capacitance at lower frequencies of the oil-paper insulation are sensitive to MCP changes. Therefore, the correlation between the parameters of the EDM branches and the dielectric response of insulation systems at lower frequencies is an underlying problem that should be well understood first before practically using the equivalent model to predict the MCP of insulation systems quantitatively. To this end, a sub-spectrum decomposition method is proposed here to study the specific correlation pattern of the frequency response between the individual branches and terminal of the model to identify the symbolic circuit elements or sub-structures which are sensitive to temperature and moisture changes.
From the perspective of circuit theory, the overall dielectric spectroscopy of the EDM (at the terminals of the circuit) consists of the dielectric spectroscopies of the branches, however, the contributions of each branch to the overall spectroscopy vary with the frequency. Referring to the model structure shown in Fig. 1 and the definitions of dielectric spectrum function of the model (1)-(2), similarly, we define the real and imaginary parts of the complex capacitance of the individual polarization branch of EDM, as shown in the following formulas (7), (8).

\[
C'(\omega) = \frac{C_i}{1 + (\omega R_i C_i)^2} \quad (7)
\]
\[
C''(\omega) = \frac{\omega R_i C_i^2}{1 + (\omega R_i C_i)^2} \quad (8)
\]

Using the calculated parameters and the above definitions (7)-(8), the dielectric spectroscopy of a single branch (sub-spectrum) can be computed or separated from the total terminal spectrum of EDM. As a case study, Fig. 14 shows the sub-spectrum of EDM branches calculated from FDS of model bushing no. 2 that was tested at a temperature of 30 °C.

The Fig. 14 reveals that the real capacitance at lower frequencies is contributed equally by the polarization branches and the \(C_0\) branch, whereas that at higher frequencies is contributed primarily by the \(C_0\) branch. The imaginary capacitance at lower frequencies is contributed by the \(R_0\) branch and polarization branches \(C_1-R_1\), \(C_2-R_2\), and \(C_3-R_3\), with negligibly small contributions of the other polarization branches, whereas that at higher frequencies is mainly contributed by polarization branches \(C_4-R_4\), \(C_5-R_5\), and \(C_6-R_6\).

Given that the imaginary capacitance curve at lower frequencies is susceptible of the moisture content of the insulation system, the MCP is thus closely related to sub-spectrum of the following EDM branches that dominate LF frequency response: \(C_0-R_0\), \(C_1-R_1\), \(C_2-R_2\), and \(C_3-R_3\). Considering this, the polarization resistance and time constants of the EDM at lower frequencies were employed in this paper to compose a set of multiple characteristic parameters to more accurately figure out MCP.

Polynomial power functions are used to fit the relationship between the featured polarization resistances \((R_1, R_2, \text{and } R_3)\) and time constants \((\tau_0, \tau_1, \tau_2, \text{and } \tau_3)\) of the EDM and the
two variables (temperature & MCP), as listed in Table 5. The fitting equations shown in Table 5 can be generalized as the following form:

\[ Y = P_1 + P_2 \cdot T^{P_3} + P_4 \cdot K_{mc}^{P_5} + P_6 \cdot T^{P_3} \cdot K_{mc}^{P_5} \]  

where \( Y \) represents the parameters of the EDM branches at lower frequencies that are used as MCP indicators \((R_1, R_2, R_3, t_0, t_1, t_2, \text{ and } t_3); T \) is the temperature, \( MCP \) is the moisture content by percentage—MCP; and \( P_1, P_2, P_3, P_4, P_5, \) and \( P_6 \) are the coefficients needs to be estimated. Once these indicators and coefficients in the seven fitting expressions are known, MCP can be back-calculated using the following equation that is derived from Equation (9):

\[ MCP = \sqrt{\frac{Y - P_1 - P_2 \cdot T^{P_3}}{P_4 + P_6 \cdot T^{P_3}}} \]  

To sum up, the moisture content of oil-paper insulation systems can be estimated by following steps: First, calculate the parameters in EDM using FDS results that are measured from the target insulation system; substitute the seven indicators of MCP, the corresponding testing temperatures into Equation (10). Then, average the MCP values obtained separately from the seven equations to determine the final MCP values. The effectiveness of the parameterized EDM in moisture content prediction was verified against FDS measurements of bushing model no. 2 at a temperature of 50°C. The moisture content estimated by the parameterized EDM was 1.84% for the bushing model, which was close to the measurement of 1.78%.

VI. CONCLUSION

To identify the moisture state of OIP insulation via interpreting the equivalent model parameters, in this paper, the extended Debye model for OIP insulation in a wide frequency band was established first by employing the genetic algorithm (GA) and Levenberg–Marquardt algorithm (LMA) to the frequency-domain spectroscopy (FDS) curves of OIP condenser bushing models at different temperatures and different levels of moisture content. The temperature and moisture content are found to affect the parameters of the equivalent model in a definite and distinct way. Separate effects of temperature and moisture were correlated with the capacitances, resistances, and time constants of single branches of the EDM from the perspective of sub-spectroscopy analysis of individual branches. Thereby, seven indicators of OIP moisture were proposed: polarization resistances \((R_1, R_2, \text{ and } R_3) \) and time constants \((t_0, t_1, t_2, \text{ and } t_3) \) of the EDM. The bivariate relationships between each of the indicators and temperature & moisture are found to conform to polynomial power functions, which enables an accurate estimate of the moisture content of oil-paper insulation at different temperatures.

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