

Article

Non-Uniform Aging Diagnosis of High-Voltage Machine Stator-Winding Insulation Using Multi-Indicator Fusion of Dielectric Spectra

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Abstract

Accurate assessment of the stator-winding insulation condition in high-voltage machines is crucial for safe operation. Conventional evaluation methods treat the insulation as spatially uniform and provide only a holistic assessment; in practice, however, degradation within the insulation wall is non-uniform, with the inner layers adjacent to the copper conductor typically deteriorating more severely. As a result, existing diagnostic approaches cannot accurately evaluate non-uniform degradation. To address this gap, this paper proposes a diagnosis method for non-uniform aging of stator-winding insulation based on multi-indicator fusion of dielectric spectroscopy. A Frequency Domain Spectroscopy (FDS) simulation model that explicitly incorporates non-uniform aging is established and experimentally validated. The validated model is then used to generate FDS responses under various non-uniform-aging scenarios, from which multiple characteristic indicators that quantify the degree of non-uniformity are extracted. Building on these indicators, a non-uniform aging evaluation method using Multi-Anchor TOPSIS is constructed for diagnosing non-uniform aging.

Keywords: frequency-domain dielectric spectroscopy; finite-element simulation; high-voltage electrical machines; non-uniform aging; Multi-Anchor TOPSIS method

1. Introduction

High-voltage motors are key equipment in power systems, and the insulation condition of their stator windings directly determines the operational reliability and service life of the entire machine. During long-term operation, the synergistic effect of multiple stresses such as electrical, thermal and mechanical stresses may lead to the non-uniform layered aging phenomenon of the main insulation of stator windings. Among these stresses, thermal stress is closely related to the through-thickness temperature gradient of stator-winding insulation. Since the copper conductor is the main heat source during operation, the insulation layer close to the conductor side generally suffers higher thermal stress and may deteriorate faster than the outer layer. Local areas suffer from severe deterioration, which is very likely to cause local breakdown and even equipment failure [1,2]. Studying the evaluation methods for the non-uniform aging of stator-winding insulation is of great significance for ensuring the safe operation of equipment.

In recent years, Frequency Domain Spectroscopy (FDS) has been widely applied in insulation condition detection of high-voltage equipment such as transformers [3,4],



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cables [5,6], and motors [7] due to its excellent anti-interference capability and spectral resolution. Compared with traditional indicators like breakdown voltage or leakage current, FDS can acquire the polarization characteristics and conductive loss information of materials within a wide frequency range, thereby accurately diagnosing the insulation aging state of stator windings. Huang Qizhao conducted thermal aging on stator bars and studied the influence of thermal aging on the dielectric response of stator windings [1]. Shan Zhiduo et al. performed electrical aging on stator bars and proposed a stator-winding insulation condition assessment method based on characteristic quantities of frequency-domain dielectric response [2]. Professor Ge Baojun and other scholars carried out multi-stress aging on stator bars and investigated the frequency-domain dielectric response characteristics during the deterioration process of stator windings under the synergistic effect of multiple stresses [8]. However, current FDS-based stator-winding insulation condition assessment methods mainly focus on the average state of the overall insulation, i.e., assuming that the insulation aging degree of the stator winding is uniform. In reality, the deterioration degree inside and outside the insulation layer of the stator winding is not completely consistent. In field conditions, there often exists a non-uniform aging state where the main insulation near the inner layer of the copper conductor deteriorates more severely. This phenomenon provides the physical basis for using layered thermal aging to approximate the non-uniform aging distribution along the insulation thickness. The average insulation condition assessment cannot effectively reflect the local deterioration characteristics, thus leading to serious hidden dangers in diagnostic results such as “overly optimistic assessment results and delayed risk identification”. Therefore, it is urgent to study the assessment method for non-uniform aging of stator windings to ensure the reliable operation of stator windings.

At present, there is still a lack of relevant research on the non-uniform aging diagnosis of stator windings in high-voltage motors, while the non-uniform aging diagnosis technology has been relatively in-depth in the oil–paper insulation system of transformers. Yao Mengxi et al. used the dielectric response method to study the non-uniform thermal aging characteristics of oil–paper insulation and revealed the differences in insulation degradation characteristics under temperature gradients [9]. Sui Bin et al. further found that the PDC curve in the local high-temperature accelerated aging area of oil–paper insulation shifted significantly upward, and proposed time-domain dielectric response characteristic parameters to evaluate the degree of non-uniform aging [10]. Liao Wei [11], Li Lu [12], Zhang Mingze [13], Gong [14], etc., have carried out extensive research on improving dielectric models and parameter inversion, but the application objects are still concentrated on oil–paper insulation. Wang Haoyue et al. [15] used high-voltage Frequency Domain Spectroscopy to study the aging and delamination phenomenon of cable insulation and proposed an indexation method to diagnose cable insulation. These research results provide a methodological basis for the non-uniform aging assessment of stator windings in high-voltage motors. However, existing studies are all aimed at transformer oil–paper insulation or cable cross-linked polyethylene insulation, and cannot be directly transferred to the epoxy–mica insulation system of stator windings. The main limitations lie in large differences in material structure, insufficient modeling accuracy, and inapplicability of evaluation indicators.

To address these issues, this paper proposes a diagnosis method for non-uniform aging of stator-winding insulation in high-voltage motors based on dielectric spectrum modeling and multi-index fusion evaluation, which mainly includes the following contents:

- (1) An FDS finite element simulation calculation model considering different thermal aging gradients of stator-winding insulation is constructed to simulate the dielectric spectrum under different non-uniform aging conditions, and the model accuracy is verified by actual measurement.

- (2) Based on the extended Davidson–Cole (DC) model, the dielectric spectra under different non-uniform aging conditions are fitted, and characteristic indicators that can effectively characterize the degree of non-uniformity are extracted.
- (3) Based on the classical TOPSIS scoring method, a Multi-Anchor improved TOPSIS incorporating four aging anchor points (H/Mi/Mo/S) is constructed to realize the evaluation of the non-uniform aging degree of stator-winding insulation.

2. Finite Element Calculation Model of Frequency Domain Spectroscopy (FDS) for Non-Uniform Aging of Stator Winding Insulation

In order to study the frequency-domain dielectric response characteristics of stator-winding insulation after non-uniform aging, it is necessary to analyze a large number of FDS curves under non-uniform aging states. However, the workload of obtaining a large amount of FDS data through experiments is too enormous, and the volatility of experimental tests will also bring interference to subsequent analysis. Therefore, to quickly obtain the non-uniform aging FDS database, after measuring and obtaining the material parameters of stator windings under different aging states in this paper, the Finite Element Method (FEM) is used to quickly expand the FDS database, and existing studies have proven the reliability of this type of research method [16].

2.1. The Principle of Frequency Domain Spectroscopy (FDS) Simulation

FDS tests on stator windings typically employ a frequency range of 1 mHz to 1 kHz [1,2]. Accordingly, this study adopts the same range for both FDS simulations and measurements. Within this band, the dimensions of the test specimen are significantly smaller than the electromagnetic wavelength, rendering magnetic induction effects negligible. Consequently, the internal electric field of the epoxy–mica insulation specimen can be approximated as an electro-quasistatic (EQS) field. Given the sinusoidal FDS excitation and the thermal equilibrium of the specimen at ambient temperature, the resulting current is correspondingly sinusoidal. By treating all field variables as time-harmonic quantities, the EQS equation is derived as follows:

$$-\nabla((\sigma + j\omega\epsilon_0\epsilon_r)\vec{E})\nabla V = 0 \quad (1)$$

where σ is the electrical conductivity, $\epsilon_0 = 8.8542 \times 10^{-12}$ F/m is the vacuum permittivity, ϵ_r is the relative permittivity of the material, ω is the angular frequency, ∇ is the gradient operator, and V is the electric potential. This governing equation has been widely used in low-frequency dielectric frequency-domain responses and electro-quasistatic finite element calculations [17].

When characterizing the frequency-domain dielectric properties of materials, the complex relative permittivity $\epsilon_r^*(\omega)$ is usually used. Therefore the frequency-domain equation of the electroquasistatic field can be obtained as:

$$-\nabla[j\omega\epsilon_0\epsilon_r^* \cdot \nabla V] = 0 \quad (2)$$

From (2), the complex impedance $Z^*(\omega)$ between the test electrode and the pressure electrode is solved. After obtaining $Z^*(\omega)$ at each frequency, the complex relative permittivity can be solved according to (3) and (4), thereby obtaining the FDS curve of the sample.

$$\begin{aligned} \epsilon_{rFEM}^*(\omega) &= \frac{-j}{\omega \cdot Z^*(\omega)} \cdot \frac{1}{C_0} \\ &= \epsilon'_{rFEM}(\omega) - j \cdot \epsilon''_{rFEM}(\omega) \end{aligned} \quad (3)$$

$$C_0 = \epsilon_0 \frac{S}{d} \quad (4)$$

where C_0 is the geometric capacitance, S is the electrode area, and d is the distance between the two electrodes, which is equal to the thickness of the sample.

2.2. Deterioration Test of Main Insulation in Stator Windings and Extraction of Material Parameters

As derived in Section 2.1, to calculate the FDS curve of insulation, the parameters of relative permittivity (ϵ_r) and conductivity (σ) of the material are required. To obtain the material parameters of the main insulation of stator bars under different aging states, samples are first taken from the slot part of newly produced stator bars of high-voltage motors with a rated voltage of 15.75 kV and insulation class F, and made into main insulation samples of 60 mm × 20 mm × 4 mm. Then, grouped thermal aging treatments are carried out, i.e., thermal aging at 180 °C for 5 d, 10 d, and 15 d respectively [18]. After aging, FDS tests are performed on the samples under various aging conditions.

The principle of FDS testing is shown in Figure 1. In this paper, a three-electrode system is used for the test. A guard ring was installed around the measuring electrode and grounded, serving as a guard electrode to suppress surface leakage currents and fringing field effects of the test specimen. The testing instrument is the IDAX 322 tester from Megger Company (Dover, UK), with a test frequency range of 1 mHz–1 kHz, a test voltage of 200 V_{pp}, and a test temperature of 20 °C. Through FDS testing, the complex relative permittivity of stator-winding insulation can be obtained, and the ϵ_r and σ of the material.

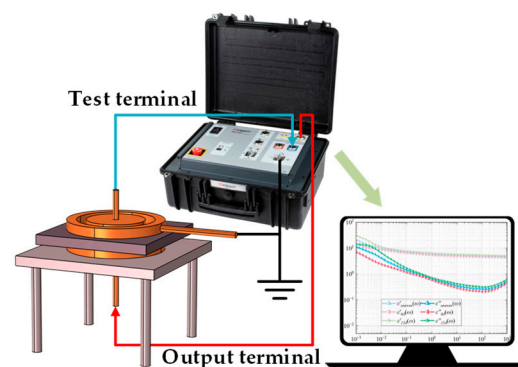


Figure 1. Wiring diagram for FDS testing.

The relative permittivity under different aging states obtained by testing is shown in Figure 2. It can be seen from Figure 2 that with the increase in thermal aging time, both the real and imaginary parts of the relative permittivity of the main insulation increase, and the change is relatively small in the high-frequency band while more obvious in the low-frequency band. This is because epoxy–mica insulation generates various polarization phenomena under an alternating electric field, and the establishment time of each type of polarization differs. Generally, in the low-frequency region with frequencies ranging from 10^{-3} Hz to 10^1 Hz, the dominant polarization type is interfacial polarization, while in the high-frequency region with frequencies above 10^2 Hz, the dominant polarization type is orientation polarization. As thermal aging time increases, the molecular bonds of epoxy resin inside the epoxy–mica insulation gradually break, resulting in degradation and embrittlement. The viscosity between mica layers decreases, which aggravates the interfacial polarization. In addition, the small molecules generated by degradation also promote the aggravation of interfacial polarization in the low-frequency region.

It should be noted that the thermal aging experiment is used to obtain the dielectric parameters of epoxy–mica insulation under different thermal deterioration degrees. It does not fully reproduce the coupled electrical–thermal–mechanical aging process in actual

machines, but provides the material basis for the subsequent layered non-uniform thermal aging model.

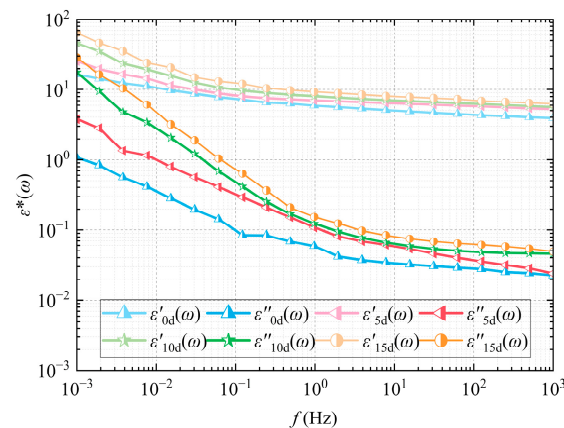


Figure 2. Relative permittivity of insulation under different aging conditions.

2.3. FDS Simulation Calculation Model for Stator-Winding Insulation Based on the Finite Element Method (FEM)

On the premise of obtaining the main insulation material parameters under different aging states in Section 2.2, this paper constructs a finite element FDS simulation calculation model as shown in Figure 3. The sample has a thickness of 4 mm and a radius of 10 mm. The voltage of the high-voltage electrode is the same as the FDS test voltage, and the low-voltage electrode is grounded. The complex impedance $Z^*(\omega)$ between the two electrodes is solved based on (2). After obtaining $Z^*(\omega)$ at each frequency, the complex relative permittivity can be solved according to (3) and (4), thereby obtaining the FDS curve of the sample.

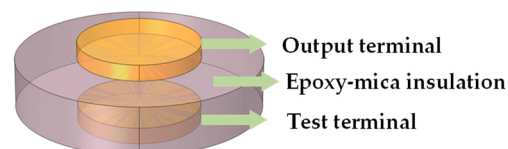


Figure 3. FDS finite element model.

To verify the feasibility and accuracy of the simulation model in this paper, the simulated values are compared with the measured values. The measured FDS curves and simulated curves under different thermal aging states are shown in Figure 4. It is not difficult to find from the figures that the degree of agreement between the simulated curves and the measured curves is very high, with only minimal differences in the low-frequency part, which verifies the accuracy of the FDS simulation calculation in this paper.

To further quantitatively analyze the error between the measured and simulated results, the correlation coefficient R^2 and mean absolute percentage error (MAPE) are used for error analysis. The correlation coefficient R^2 can reflect the goodness of fit of the simulated data to the measured data, and its calculation formula is shown in (5). The R^2 values under four simulation cases are shown in Table 1.

$$R^2 = 1 - \frac{\sum_{i=1}^n |\varepsilon(\omega) - \hat{\varepsilon}(\omega)|^2}{\sum_{i=1}^n \left| \varepsilon(\omega) - \frac{1}{n} \sum_{i=1}^n \hat{\varepsilon}(\omega) \right|^2} \quad (5)$$

where $\varepsilon(\omega)$ is the measured data, and $\hat{\varepsilon}(\omega)$ is the simulated data.

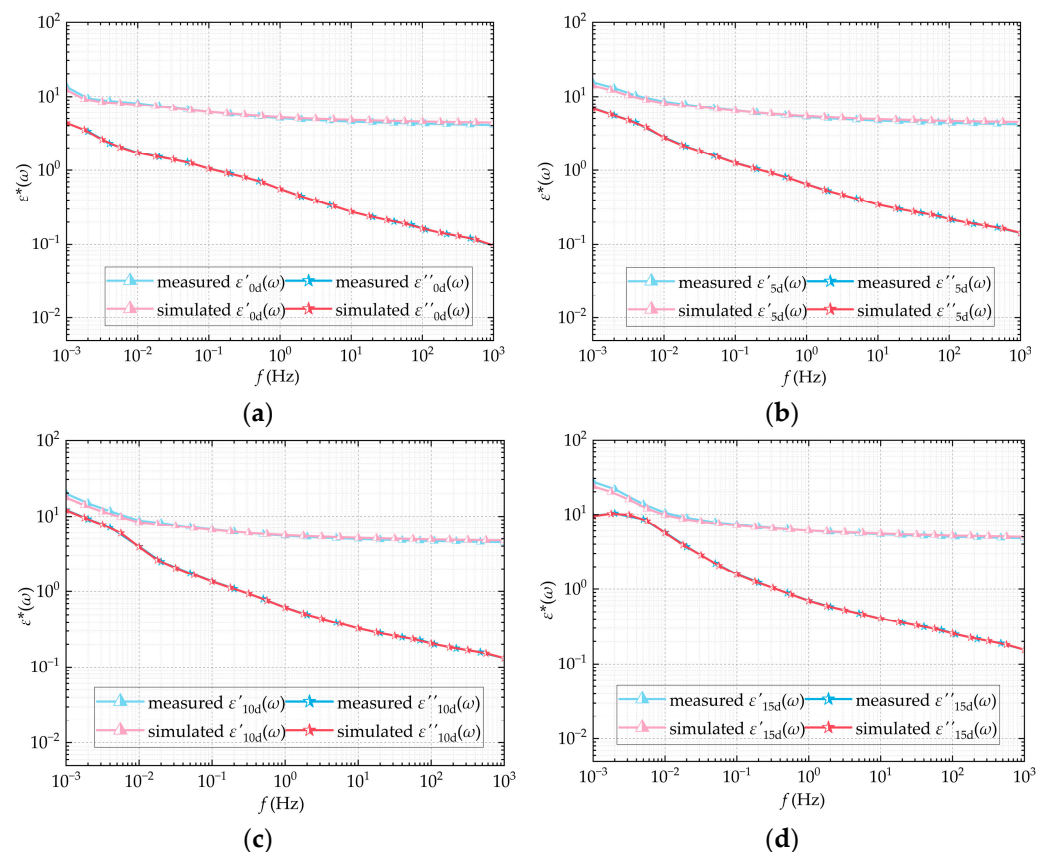


Figure 4. Comparison of experimental and simulated FDS results: (a) 0 days of thermal aging; (b) 5 days of thermal aging; (c) 10 days of thermal aging; (d) 15 days of thermal aging.

Table 1. R^2 Analysis between measured and simulated results.

R^2	ϵ'	ϵ''
Thermal Aging 0 d	0.9707	0.9999
Thermal Aging 5 d	0.9632	0.9999
Thermal Aging 10 d	0.9623	0.9999
Thermal Aging 15 d	0.9609	0.9999

MAPE is the average value of the percentage of the absolute error between the simulated value and the measured value relative to the measured value, which can reflect the accuracy of the simulation. Its calculation formula is shown in (6), and the MAPE of the four simulation cases is shown in Table 2.

$$\text{MAPE} = \frac{1}{n} \sum \left| \frac{\epsilon(\omega) - \hat{\epsilon}(\omega)}{\epsilon(\omega)} \right| \times 100\% \quad (6)$$

Table 2. MAPE analysis between measured and simulated results.

MAPE	ϵ'	ϵ''
Thermal Aging 0 d	5.2015	0.2889
Thermal Aging 5 d	4.1096	0.4640
Thermal Aging 10 d	5.2762	0.6262
Thermal Aging 15 d	6.5928	0.7282

As observed from Tables 1 and 2, the discrepancy between the simulated and measured results is extremely small, indicating that the proposed FDS calculation method exhibits

high accuracy and is capable of simulating the frequency-domain dielectric response of insulation.

2.4. FDS Simulation Model and Validation Considering Non-Uniform Aging

To simulate the frequency-domain dielectric response of the non-uniform aging state of epoxy–mica insulation in stator bars, a non-uniform aging model as shown in Figure 5 is established. Multiple layers of epoxy–mica insulation with different aging states are used to simulate the equivalent non-uniform thermal aging state of bar insulation. In the simulation model, the voltage of the high-voltage electrode is the same as that used in the FDS test, and the low-voltage electrode is grounded. Each layer of epoxy–mica insulation has a thickness of 4 mm and a radius of 10 mm. The material parameters from the high-voltage electrode to the low-voltage electrode correspond to those of thermal aging for 15 days, 10 days, 5 days, and 0 days, respectively. This arrangement is used to approximate the aging gradient from the copper conductor side to the outer insulation side. The layer with a longer thermal aging time represents the insulation region closer to the conductor, while the layer with a shorter aging time represents the region farther from the heat source. In addition, considering the possible interfacial gaps between individual epoxy–mica samples, an air gap of 0.1 mm is set between each layer in the simulation as an equivalent interfacial layer.

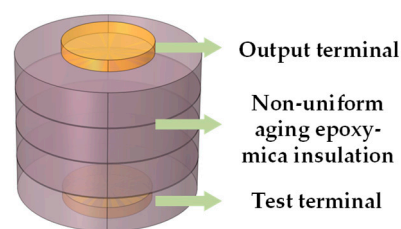


Figure 5. FDS-based simulation model of insulation under non-uniform aging.

To verify the effectiveness of this model, FDS tests are conducted on epoxy–mica insulation samples with different aging states arranged in the same manner. The test temperature, test voltage, and test frequency range are all consistent with those in the simulation model. The comparison between the test results and simulation results is presented in Figure 6, where R^2 is 0.9976, and the mean absolute percentage errors (MAPE) of ϵ' and ϵ'' are 4.5928 and 6.2758, respectively.

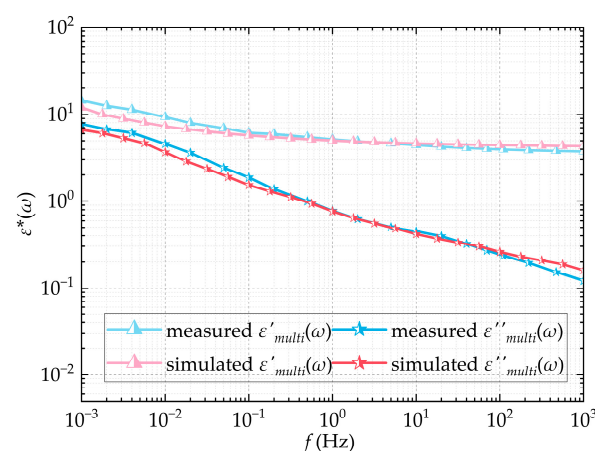


Figure 6. Comparison between FDS experimental and simulation results of the composite model.

As can be observed from Figure 6 and fitting indicators, although there is a certain discrepancy between the simulation results and test results, the overall trend of the curves

is basically consistent. The deviation may be attributed to the relatively large and randomly distributed air gaps between multi-layer samples in actual tests, which leads to deviations between test results and simulation results in the low-frequency region. In addition, there are multiple interferences during the FDS test, the test instruments have certain errors, and rounding errors also occur during data processing. Therefore, within the error range, this simulation model can reasonably reproduce the main trend of the FDS curve of non-uniformly aged insulation. The influence of stochastic interfacial defects will be further considered in future model improvement.

3. Analysis of Frequency-Domain Dielectric Response Under Non-Uniform Aging of Main Insulation

To study the frequency-domain dielectric response characteristics of stator-winding insulation under different non-uniform aging conditions and thereby accurately extract characteristic indicators that can characterize non-uniformity, it is necessary to extract the FDS curve characteristics under various non-uniform aging states. Based on the non-uniform thermal aging simulation model in Section 2.4, the non-uniform aging FDS database is expanded. This method can realize the controllable adjustment of the number of aging layers, thickness ratio, and arrangement order, and avoid the interference of uncontrollable factors in experiments, which can greatly improve the simulation efficiency. Based on the non-uniform aging FDS database, the modified Davidson–Cole (DC) model parameters that can characterize non-uniform aging are further extracted.

3.1. Model Parameter Identification Based on the Modified DC Model

Existing studies have shown that the Davidson–Cole (DC) model can well fit the dielectric response characteristics of epoxy–mica insulation in stator windings [19]. However, the slope of the low-frequency segment of the frequency-domain dielectric spectrum obtained in this study changes significantly. Therefore, this paper uses a DC model modified with DC conductance and hopping conductance for model fitting, as shown in (7) [20].

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{(1 + j\omega\tau)^\beta} + \frac{\zeta}{\varepsilon_0(j\omega)^n} + \frac{\sigma_{dc}}{j\omega\varepsilon_0} \quad (7)$$

where $\varepsilon^*(\omega)$ is the complex permittivity, $\omega = 2\pi f$ is the angular frequency, and f is the signal frequency. ε_s is the static permittivity, and ε_∞ is the optical frequency permittivity. τ is the relaxation time, representing the time scale of the polarization process. β is a distribution parameter ($0 < \beta \leq 1$) that controls the distribution width of the relaxation process. ζ is an amplitude coefficient related to ionic conduction or interfacial polarization, used to simulate non-ideal polarization behavior. ε_0 is the vacuum permittivity, approximately 8.854×10^{-12} F/m. n is an exponential term, used to characterize the response related to heterogeneous interfaces or electrode effects, generally taking $0 < n < 1$. σ_{dc} is the DC conductivity.

Utilizing the non-uniform thermal aging simulation model in Section 2.4, various aging conditions are simulated to acquire FDS curves, which are then fitted with the modified DC model. In this work, the built-in `lsqcurvefit` function in MATLAB R2023b is adopted for model fitting. The trust-region-reflective algorithm was used in `lsqcurvefit`. According to the physical meanings of the parameters in the modified DC model, the parameter constraints were set within reasonable ranges: ε_s , ε_∞ , τ , ζ , and σ_{dc} were constrained to be positive values, β was limited to $0 < \beta < 1$, and n was limited to $0 < n < 1$. The initial values of the parameters were determined based on the fitting results of uniformly aged samples and then adjusted within the corresponding parameter bounds. The maximum number of iterations was set to 10,000, and both the function tolerance and step tolerance were set to

10^{-12} . The fitting process was terminated when the convergence criteria of lsqcurvefit were satisfied and the MAPE was lower than 5%. The specific non-uniform aging settings and corresponding modified DC model parameters are detailed in Table 3.

Table 3. Fitting results of FDS under different non-uniform aging conditions.

Non-Uniform Aging Conditions	ε_s	ε_∞	τ	β	ζ	n	σ_{dc}
0-0-5-5	14.005	1.085	77.227	0.531	3.699×10^{-11}	0.035	2.365×10^{-12}
0-0-10-10	40.248	5.199	150.357	0.471	2.544×10^{-11}	0.071	0.915×10^{-12}
0-0-15-15	28.679	5.553	55.898	0.427	1.151×10^{-11}	0.041	1.333×10^{-12}
5-5-10-10	31.846	5.538	93.563	0.594	6.351×10^{-11}	0.146	3.316×10^{-12}
5-5-15-15	36.658	0.219	98.782	0.571	2.639×10^{-11}	0.021	2.354×10^{-12}
10-10-15-15	54.528	5.781	144.338	0.583	6.512×10^{-11}	0.091	0.985×10^{-11}
0-0-5-10	29.360	5.838	131.358	0.479	1.354×10^{-11}	0.190	1.226×10^{-12}
0-5-15	31.583	5.371	137.764	0.437	1.534×10^{-11}	0.070	1.06×10^{-12}

3.2. Evaluation Method for the Non-Uniformity of Stator-Winding Insulation

After obtaining the fitting results of FDS curves under different non-uniform aging conditions in Section 2.1, it is necessary to further quantify the degree of non-uniform aging and explore the functional relationship between the modified DC model parameters and the non-uniformity to establish a non-uniform aging evaluation method based on multi-index fusion.

3.2.1. Selection of Characteristic Parameters

The insulation is divided into m layers, each exhibiting a uniform aging state. For the FDS data of each layer, denoted as $X^{(i)} = \{X_1^{(i)}, X_2^{(i)}, \dots, X_n^{(i)}\}$ ($i = 1, 2, \dots, m$), the standard deviation of the first-order difference, $\sigma^{(i)}$, is calculated as presented in (8).

$$\sigma^{(i)} = \sqrt{\frac{1}{n_i - 2} \sum_{t=2}^{n_i} (\Delta X_t^{(i)} - \mu^{(i)})^2} \quad (8)$$

where $\Delta X_t^{(i)}$ is the first-order difference in the FDS data $X^{(i)}$, and $\mu^{(i)}$ is the mean value of $X^{(i)}$.

The Coefficient of Variation (CV) is a statistical measure of the relative dispersion of data points. In this paper, the CV of the standard deviation of the first-order differences is defined as the degree of non-uniformity under the corresponding condition, which is calculated as shown in (9).

$$CV = \frac{\sigma_s}{\mu_s} = \frac{\sqrt{\frac{1}{m-1} \sum_{i=1}^m (\sigma^{(i)} - \mu_s)^2}}{\frac{1}{m} \sum_{i=1}^m \sigma^{(i)}} \quad (9)$$

where σ_s denotes the standard deviation of $\sigma^{(i)}$, and μ_s represents the mean value of $\sigma^{(i)}$.

By fitting the non-uniformity of the modified DC model under various conditions, it is observed that three characteristic parameters—the inhomogeneity coefficient β , the hopping conductivity ζ , and the DC conductivity σ_{dc} —exhibit distinct functional relationships with non-uniformity. As shown in Figure 7a, the inhomogeneity coefficient β follows a linear relationship with non-uniformity. β characterizes the broadening of the dielectric relaxation time distribution. With increasing discrepancies in dielectric parameters and relaxation behaviors among different aged layers, the overall dielectric response shifts from a single

or concentrated relaxation process to a broader distribution. Consequently, within the simulated non-uniform aging range in this paper, β varies monotonically and stably with increasing non-uniformity, allowing for an approximate linear description.

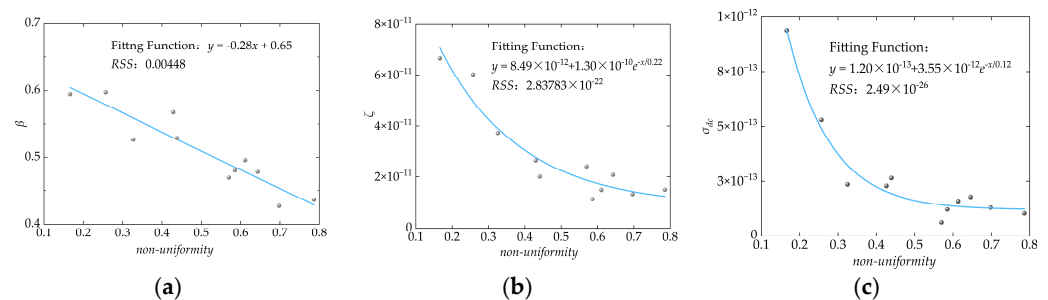


Figure 7. Characteristic parameter fitting curves. (a) Non-uniformity factor β ; (b) hopping conductance ζ ; (c) DC conductance σ_{dc} .

As shown in Figure 7b,c, both the hopping conductivity ζ and the DC conductivity σ_{dc} exhibit exponential relationships with non-uniformity, respectively. This is because ζ is primarily related to non-ideal polarization and hopping conduction processes in the low-frequency range, whereas σ_{dc} reflects the enhancement of equivalent DC conduction channels. As non-uniformity increases, the discrepancies in permittivity, electrical conductivity, and relaxation time among different aged layers further widen. Consequently, charge accumulation and interfacial polarization at the inter-layer interfaces are strengthened, making the low-frequency dielectric loss and equivalent conductance responses more sensitive to variations in non-uniformity.

From the perspective of material aging mechanisms, epoxy–mica insulation is an organic–inorganic composite insulation system, and variations in its dielectric spectra are closely related to the epoxy resin matrix, mica layers, inter-layer interfaces, and defect structures. During thermal aging, the epoxy resin matrix undergoes molecular chain scission, oxidation, and cross-linked network degradation, leading to resin embrittlement, weakened bonding at the mica–resin interface, and the formation of more micro-pores, interfacial defects, and charge traps. For structures with non-uniform aging along the thickness direction, material parameters vary among different aged layers. Consequently, Maxwell–Wagner–Sillars (MWS) interfacial polarization is more likely to occur at the layer interfaces, further enhancing the low-frequency dielectric response. In summary, β primarily reflects the broadening of the relaxation time distribution, ζ characterizes the low-frequency polarization behavior associated with hopping conduction and non-ideal interfacial responses, and σ_{dc} indicates the enhancement of equivalent conduction channels and DC conduction losses. Consequently, these three parameters of the modified DC model can be utilized to characterize the non-uniform aging state of the stator-winding insulation.

3.2.2. Non-Uniformity Evaluation Method Based on Multi-Anchor TOPSIS

To comprehensively consider the importance of the three characteristic parameters in evaluating material performance, an improved TOPSIS comprehensive assessment method is adopted to establish a non-uniform aging scoring model. This enables the multi-parameter fusion diagnosis of the non-uniformity factor β , the hopping conductance ζ , and the DC conductance σ_{dc} .

Since β increases linearly with degradation, while ζ and σ_{dc} increase exponentially, a logarithmic transformation is first applied to ζ and σ_{dc} . Subsequently, a sample vector is constructed as $\mathbf{x} = [\beta, \ln \zeta, \ln \sigma_{dc}]^T$. Let the anchor points for the four aging levels be:

$$\mathbf{v}_H, \mathbf{v}_{Mi}, \mathbf{v}_{Mo}, \mathbf{v}_S \in \mathbb{R}^3 \quad (10)$$

these correspond to the representative values in the feature space for “Healthy, Mild, Moderate, Severe,” respectively. Any sample to be evaluated is denoted as $\mathbf{x} = [\beta, \ln \zeta, \ln \sigma_{dc}] \in \mathbb{R}^3$.

A linear transformation based on “quantile scaling + weighting” is performed:

$$\begin{cases} \tilde{\mathbf{x}} = \mathbf{W}^{1/2} \mathbf{S}^{-1} (\mathbf{x} - \mathbf{c}) \\ \tilde{\mathbf{v}}_\ell = \mathbf{W}^{1/2} \mathbf{S}^{-1} (\mathbf{v}_\ell - \mathbf{c}) \\ \ell \in \{H, \text{Mi}, \text{Mo}, S\} \end{cases} \quad (11)$$

where $\mathbf{c} = (\mathbf{v}_H + \mathbf{v}_S)/2$ is the center vector, $\mathbf{S} = \text{diag}(s_\beta, s_{\ln \zeta}, s_{\ln \sigma})$ is the scaling diagonal matrix, and $\mathbf{W} = \text{diag}(w_\beta, w_{\ln \zeta}, w_{\ln \sigma})$ represents the engineering weights.

The Healthy and Severe anchor points are mapped to the ideal and anti-ideal solutions:

$$\mathbf{v}^+ = \tilde{\mathbf{v}}_H, \mathbf{v}^- = \tilde{\mathbf{v}}_S \quad (12)$$

the weighted Euclidean distance under the aforementioned metric for any sample is:

$$d^+(\mathbf{x}) = \|\tilde{\mathbf{x}} - \mathbf{v}^+\|_2, d^-(\mathbf{x}) = \|\tilde{\mathbf{x}} - \mathbf{v}^-\|_2 \quad (13)$$

define the closeness coefficient:

$$C^*(\mathbf{x}) = \frac{d^-(\mathbf{x})}{d^+(\mathbf{x}) + d^-(\mathbf{x})} \in (0, 1) \quad (14)$$

Classical Topsis uses only (h, s) . To leverage the nonlinear trajectory information from (Mi, Mo), a polyline trajectory is constructed in the normalized space:

$$\mathcal{P} = [\mathbf{v}^+ \rightarrow \tilde{\mathbf{v}}_{\text{Mi}} \rightarrow \tilde{\mathbf{v}}_{\text{Mo}} \rightarrow \mathbf{v}^-] \quad (15)$$

denoting these segments of the polyline, a $\overline{\mathbf{p}_0\mathbf{p}_1}, \overline{\mathbf{p}_1\mathbf{p}_2}, \overline{\mathbf{p}_2\mathbf{p}_3}$, where $\mathbf{p}_0 = \mathbf{v}^+, \mathbf{p}_1 = \tilde{\mathbf{v}}_{\text{Mi}}, \mathbf{p}_2 = \tilde{\mathbf{v}}_{\text{Mo}}, \mathbf{p}_3 = \mathbf{v}^-$.

Project $\tilde{\mathbf{x}}$ onto the nearest point on the polyline $\mathcal{P}$, obtaining the projection point $\Pi(\tilde{\mathbf{x}})$ and the arc length parameter $t(\mathbf{x})$:

$$t(\mathbf{x}) = \frac{\widehat{\mathbf{p}_0}}{\widehat{\mathcal{P}}} \in [0, 1] \quad (16)$$

where $\widehat{\mathbf{p}_0}$ is the arc length along the polyline from $\mathbf{p}_0$ to $\Pi(\tilde{\mathbf{x}})$, $\widehat{\mathcal{P}}$ is the total arc length of the polyline. Simultaneously, define the lateral deviation:

$$r_\perp(\mathbf{x}) = \|\tilde{\mathbf{x}} - \Pi(\tilde{\mathbf{x}})\|_2 \quad (17)$$

use t to perform a monotonic and consistent piecewise calibration, correcting nonlinearity on C^* , where $\phi : [0, 1] \rightarrow [0, 1]$ is a piecewise linear/spline function satisfying $\phi(C^*(\mathbf{p}_k)) = 1 - \frac{k}{3}$.

This aligns the C^* values of the four anchor points with the ordered health degrees $[1, 2/3, 1/3, 0]$ yielding a strictly monotonic calibration function ϕ that passes through (H, Mi, Mo, S).

To suppress outliers that deviate significantly from the degradation trajectory (e.g., an indicator being abnormally large), a lateral penalty is introduced for $\hat{C}$.

$$C_{\text{MA}}(\mathbf{x}) = \frac{\hat{C}(\mathbf{x})}{1 + \lambda \frac{r_\perp(\mathbf{x})}{L}} \quad (\lambda \geq 0) \quad (18)$$

where $\bar{L}$ is a scaling term based on the average length of the three polyline segments (ensuring dimensionless), and λ is the penalty coefficient, taken as $\lambda = 0.2$ in this paper.

Transform CMA into a 0–100 score using a linear or mild S-shaped mapping:

$$IHS = 100C_{MA} \quad (19)$$

The engineering grading thresholds are given as: Healthy: $IHS \geq 85$; Attention: $70 \leq IHS < 85$; Degraded: $50 \leq IHS < 70$; Critical: $IHS < 50$.

This paper improves upon the classical TOPSIS ideal/anti-ideal closeness coefficient by constructing a Multi-Anchor TOPSIS incorporating four aging anchor points (H/Mi/Mo/S). The method first defines a metric space using quantile scaling and engineering weights. Then, the closeness coefficient C^* is calculated using Healthy and Severe as endpoints. Subsequently, a comprehensive closeness coefficient CMA is obtained through piecewise calibration passing through the Mild/Moderate anchor points and lateral residual penalty. The final health score $IHS = 100 * CMA$ is monotonically non-increasing with aging degree. It can explicitly characterize abnormal patterns deviating from the typical degradation trajectory, making it suitable for engineering assessment and academic comparison in small-sample scenarios.

4. Conclusions

The stator-winding insulation of high-voltage motors is highly susceptible to non-uniform aging during long-term operation. Traditional Frequency Domain Spectroscopy (FDS) diagnostic methods, which rely primarily on global response characteristics, struggle to accurately identify localized deterioration regions, thereby posing significant risks of misdiagnoses and missed detections. To address this issue, this paper proposes a novel approach based on dielectric spectroscopy modeling and multi-indicator fusion evaluation. This method provides an effective means for the early detection and condition assessment of non-uniform aging in stator-winding insulation. The main conclusions are drawn as follows:

- (1) The Finite Element Method (FEM) enables the rapid computation of FDS curves for stator-winding insulation under both uniform and non-uniform thermal aging conditions, thereby facilitating the expansion of the frequency-domain dielectric response database for non-uniformly aged insulation.
- (2) The fitting results demonstrate that three characteristic parameters of the modified DC model—namely, the non-uniformity parameter β , the hopping conductivity ζ , and the DC conductivity σ_{dc} —exhibit a pronounced functional relationship with the degree of non-uniformity. Consequently, these parameters can be effectively utilized to characterize the non-uniform aging state of the stator-winding insulation.
- (3) A non-uniform aging assessment method based on Multi-Anchor TOPSIS is proposed to fuse β , ζ , and σ_{dc} , providing a comprehensive scoring framework for the non-uniform aging condition of stator windings.

The proposed method mainly focuses on the non-uniform thermal aging caused by the temperature gradient along the insulation thickness. The effects of coupled electrical–thermal–mechanical stresses and randomly distributed interfacial defects will be further investigated in future work.

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