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Hongwei Li¹, Xin Zhi^{1,*}, Dong Yang¹, Lixia Yang²,
Junmin Zhu¹ and Yongqiang Kang²

¹ School of Automation and Electrical Engineering, Lanzhou Jiaotong University, Lanzhou, 730070, China

² School of New Energy and Power Engineering, Lanzhou Jiaotong University, Lanzhou, 730070, China

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ABSTRACT

Metallized polypropylene film capacitors (MFCs) undergo dielectric aging under thermal stress, critically affecting operational reliability. To address the insufficient sensitivity of traditional loss-detection methods for early warning, this paper employs frequency-domain dielectric spectroscopy (FDS) to conduct accelerated aging tests on 100 μF automotive-grade MFCs at 120°C. The dielectric loss tangent ($\tan \delta$) and capacitance were measured over a wide frequency range (50 Hz–12 kHz). A characteristic frequency of 8100 Hz is identified as an early-warning indicator for thermal aging: while traditional methods detect only 0.7% and 2.5% changes after 360 and 720 h aging respectively, FDS captures 13.68% and 27.5% signal changes at 8100 Hz, reaching 55.5% at capacitor failure (1080 h)—3–8 times more sensitive than conventional approaches. Further analysis reveals frequency-dependent degradation patterns: the low-frequency band reflects increased conductive loss from electrode corrosion, the mid-frequency band shows the most sensitive relaxation loss changes, while high-frequency changes are slower, collectively reflecting progressive aging from interface to bulk. A health index (HI) model integrating multiple spectral features is developed using an improved weighted fusion algorithm, enabling aging state classification into four levels and remaining lifetime prediction with error within 5.6%. This FDS-based $\tan \delta$ spectral analysis provides a novel approach for MFC lifetime prediction and early aging warning, offering practical significance for enhancing electric drive system reliability in new energy vehicles.

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1 Introduction

Driven by the “dual carbon” goals, the electrification transformation of the transportation sector has become a core strategy for global emission reduction. The explosive growth of electric vehicles (EVs) has placed stricter demands on the efficiency, range, and reliability of capacitors, electric drives, and electronic control systems. As a common component in the three-electric system, improving and effectively monitoring the electrical performance of capacitors has gradually become a key factor in enhancing the overall efficiency of the three-electric system [1–3]. MFCs due to their low loss, low heat generation, self-healing capability, compact size, and suitability for high-frequency applications, have

*Correspondence: Xin Zhi (17863933067@163.com). This is an article distributed under the terms of the Creative Commons BY-NC-SA license

become one of the commonly used capacitor types in on-board inverters [4,5]. During their application, MFCs inevitably operate under high-temperature and harsh conditions for extended periods. High temperatures greatly affect the capacitance decay, charge/discharge efficiency, and dielectric properties of MFCs, potentially causing metal film breakdown leading to damage or explosion and ultimately failure, which poses risks to the safe and reliable operation of new energy vehicles [6]. Therefore, accurately assessing the aging state of MFCs under thermal stress is of significant importance for ensuring the safe and stable operation of new energy vehicles.

Currently, there are relatively mature methods for state monitoring of MFCs, which can be divided into offline monitoring and online monitoring methods. In offline monitoring, the bridge method, as a traditional measurement technique, lacks dynamic monitoring capability and can usually only monitor under fixed conditions, such as frequency and temperature, which may lead to misjudgments about the health state of MFCs. As a result, its practical application is limited. The equivalent circuit parameter identification method, another offline monitoring technique, evaluates the health state of the capacitor by establishing its equivalent circuit model and identifying its circuit parameters. This method estimates the equivalent series resistance (ESR) and capacitance value of the capacitor using the least squares algorithm for curve fitting, but it requires strict testing conditions and system disconnection during testing [7,8]. References [9,10] introduce a method by injecting controlled AC current into the system circuit and using digital filters to extract the AC ripple voltage and current components induced on the DC output, in order to monitor the ESR value. However, this method adds additional losses to the system. Reference [11] introduces Neural-inspired HTM-based online capacitor aging detection, used for aging detection of DC link capacitors in power electronic converters. Reference [12] introduces the Remaining Useful Life Prediction Method Based on CNN-LSTM Network for Capacitor Aging State Assessment. Reference [13] utilized particle filter approaches for degradation modeling and RUL prediction of electrolytic capacitors under thermal overstress conditions. These data-driven approaches demonstrate promising results but require large amounts of training data and may lack physical interpretability of the degradation mechanisms.

For online monitoring, References [14,15] combine the ESR and capacitance parameters to evaluate the state of the capacitor, improving the reliability of state monitoring results. Reference [16] proposes a method to calculate the ESR of MFCs using band energy, which can detect MFCs in the polypropylene film melting state. However, both methods simplify the equivalent model, which is not conducive to fault type identification. References [17,18] propose a method based on multi-frequency dielectric loss detection, which can determine the equivalent parallel resistance by analyzing the multi-frequency dielectric loss curve and detect MFCs at risk of self-healing failure. However, this method overlooks the impact of external forces on MFCs' dielectric loss changes and only provides results through simulation without considering the environmental complexity during the experiment.

Capacitance loss is commonly used as a key parameter to quantitatively describe the loss in capacitance. When the capacitance loss of MFCs exceeds 5%–20%, the reliability of the capacitor's electrical performance significantly decreases during each charge and discharge cycle. Therefore, when capacitance loss exceeds 5%–20%, it is considered the standard for capacitor lifetime termination. Research on online monitoring methods or state evaluation methods for capacitors generally uses parameters such as capacitance, partial discharge index, and insulation resistance to characterize capacitor failure [19]. However, after aging, these methods exhibit poor sensitivity in the early stages of aging, and the decline in parameters is not strictly linearly related to the aging degree. Different failure modes may exhibit similar parameter changes, making it difficult to differentiate [20].

FDS is widely used in online monitoring of equipment such as cables and transformers, which measures the characteristic parameters of equipment under different frequency bands of an AC electric field. It can reflect the aging causes and the degree of insulation. Reference [21] provided a comprehensive review of dielectric spectroscopy applications in HV power equipment diagnostics, demonstrating that FDS can obtain dielectric response functions offering much more information to judge the actual state of insulation materials. When metallized film capacitors experience thermal aging, temperature increases or decreases can lead to degradation of the dielectric material and metal electrode, resulting in a decline in insulation resistance. FDS technology enables sensitive detection of early thermal aging in metallized film capacitors by analyzing changes in wide-frequency dielectric characteristics, distinguishing aging types, and compensating for temperature. Combined with analysis of the loss $\tan \delta$, it can correlate with the microscopic degradation mechanisms of the material, offering the advantage of being non-destructive and clearly mechanistic, providing significant advantages over traditional monitoring methods [22,23].

To address the issue of insufficient sensitivity and difficulty in providing timely early warnings of aging in traditional capacitor aging monitoring methods, this paper proposes the use of FDS to evaluate the aging characteristics of capacitors at different aging stages. Through the establishment of an accelerated thermal aging experimental platform, the aging characteristics of metallized film capacitors are studied at different frequencies and aging times using FDS technology based on $\tan \delta$ and capacitance loss values. Experimental data is used to establish characteristic relationships between the dielectric loss and aging time of capacitors, revealing the variation patterns of capacitance loss and dielectric loss factor at 120°C. Finally, a health index evaluation model is constructed by integrating multi-frequency spectral features, achieving quantitative grading of the aging state and remaining lifetime prediction, providing a theoretical basis and precritical method for state monitoring and maintenance decisions of MFCs.

The main contributions of this work are as follows: (1) The characteristic frequency of 8100 Hz is identified as an early-warning indicator for MFC thermal aging, providing significantly enhanced detection sensitivity compared to conventional capacitance loss methods. (2) The polarization loss evolution mechanism under thermal stress is revealed, demonstrating that thermal aging intensifies dielectric defects and polarization hysteresis, leading to frequency-dependent relaxation loss changes. (3) A multi-spectral feature health index (HI) model with an improved weighted fusion algorithm is developed for aging state classification and lifetime prediction, combining entropy-based weighting with adaptive adjustment to overcome the limitations of single weighting methods.

2 Experimental Design

2.1 Experimental Principles

The dielectric constant, as a key indicator quantifying the energy storage capability of materials, is directly related to the polarization dynamics of charge carriers [24]. According to Debye relaxation theory, the physical properties of the dielectric constant need to be represented in a complex form [25]. Under the influence of an alternating electric field, the dielectric constant of polypropylene (PP) film exhibits frequency dependence, and its expression is as follows:

$$\varepsilon(\omega) = \varepsilon' - j\varepsilon'' = \varepsilon_{\infty} + \frac{\varepsilon_r - \varepsilon_{\infty}}{1 + j\omega\tau} \quad (1)$$

where, ω represents the angular frequency of the applied electric field; ε_{∞} is the relative dielectric constant of the instantaneous polarization; τ is the relaxation time constant of the polarization; and ε_r is the static relative dielectric constant ($\varepsilon_r > \varepsilon_{\infty}$). The real part of the dielectric constant, ε' reflects

the material's ability to store electrical energy, while the imaginary part, ε'' represents the dielectric loss factor, which is related to the energy dissipation of the material under the influence of the electric field [26,27]. Its expression is as follows:

$$\varepsilon'(\omega) = \varepsilon_{\infty} + \frac{\varepsilon_r - \varepsilon_{\infty}}{1 + (\omega\tau)^2} \quad (2)$$

$$\varepsilon''(\omega) = (\varepsilon_r - \varepsilon_{\infty}) \frac{\omega\tau}{1 + (\omega\tau)^2} \quad (3)$$

The ratio of ε'' to ε' is defined as the dielectric loss factor $\tan \delta$, which is expressed as:

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} \quad (4)$$

Dielectric loss refers to the energy dissipation phenomenon in a capacitor under the influence of an alternating electric field, caused by factors such as the conductive effects of the dielectric material and dielectric polarization lag [28]. The loss $\tan \delta$ is a key parameter for quantifying the degree of dielectric loss, and its value directly reflects the electrical performance of the capacitor. A smaller $\tan \delta$ value indicates lower dielectric loss and better capacitor performance [29]. Therefore, the loss tangent has become an important diagnostic indicator for evaluating the degree of degradation and aging of insulating materials in electrical equipment. The schematic diagram of its measurement principle is shown in Fig. 1:

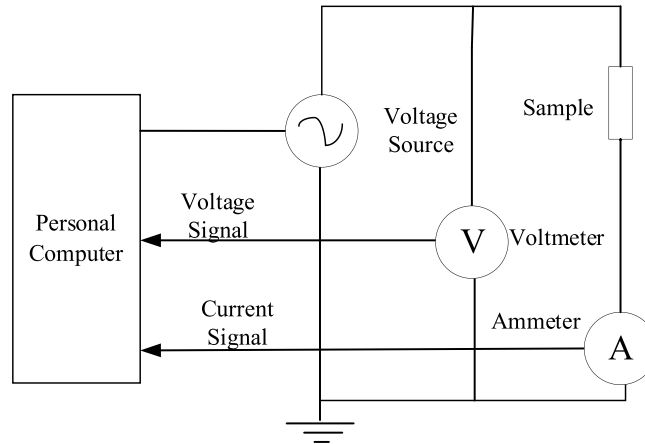


Figure 1: Measurement principal diagram

First, the changes in capacitance and dielectric loss factor $\tan \delta$ at different aging stages were measured. Then, the dielectric loss factors corresponding to capacitance tolerances of 0%, 0.7%, 2.5%, and 5% were selected to construct a feature parameter set that characterizes different aging degrees [30]. The relationship between capacitance tolerance and the characteristic $\tan \delta$ values was established, and this relationship was used as a basis to compare the measured $\tan \delta$ value of the capacitor with the characteristic values corresponding to specific tolerance intervals, thereby diagnosing the capacitor's specific aging state.

2.2 Experimental Samples and Equipment

To obtain the dielectric loss behavior of MFCs during the thermal aging process, accelerated thermal aging experiments were conducted in this study. The MFC used in the experiments was the C4AQ series C4AQIEW6100A3BJ polypropylene metallized film capacitor from Digi-Key Electronics, USA. These capacitors have a rectangular plastic box design and use four tinned leads. The specific parameters of the capacitor samples are shown in Table 1. Fig. 2 illustrates the basic structure of the capacitor.

Table 1: Capacitor parameters

Category	Value
Capacitance	100 μ F
Equivalent Series Resistance (ESR)	1.9 Mohm
Rated voltage (DC)	800 V
Temperature	$-55^{\circ}\text{C} \sim 120^{\circ}\text{C}$
Dielectric material	Polypropylene (PP), Metallized
Dimensions	57.50 mm $\times$ 45.00 mm

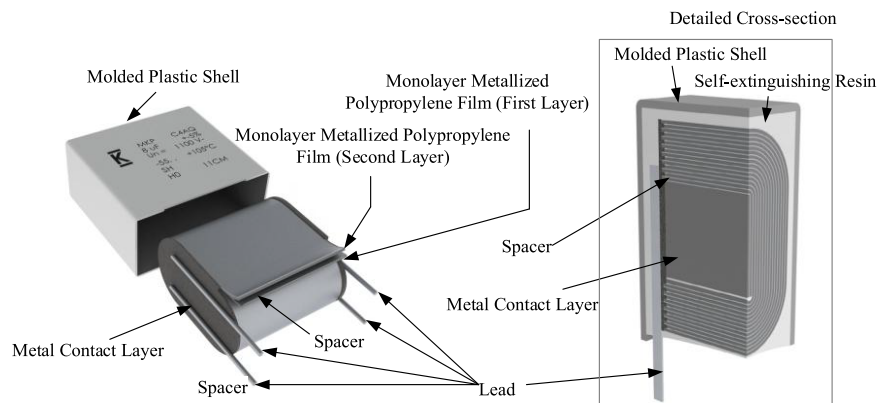


Figure 2: Sample structure

The accelerated thermal aging experimental platform uses the ST-401AAC rubber high-temperature aging test chamber from Xiamen Yishite Instrument Co., Ltd., with a controllable temperature range of 0°C to 200°C . In this study, to achieve accelerated thermal aging, the temperature was raised to 120°C , and capacitors were subjected to accelerated aging for different durations.

To measure the specific aging process of the capacitors, frequency-domain dielectric spectroscopy testing was conducted using the Concept 80 device from NOVOCONTROL GmbH (Germany). The testing environment is shown in Fig. 3. The usable frequency range of the device is 50 Hz to 100 MHz. To improve measurement accuracy and avoid switching frequency interference, the test frequency was set between 50 Hz and 12 kHz in this study. The wide-frequency dielectric spectrometer was used to test the dielectric and capacitance characteristics of the samples treated with different aging times.

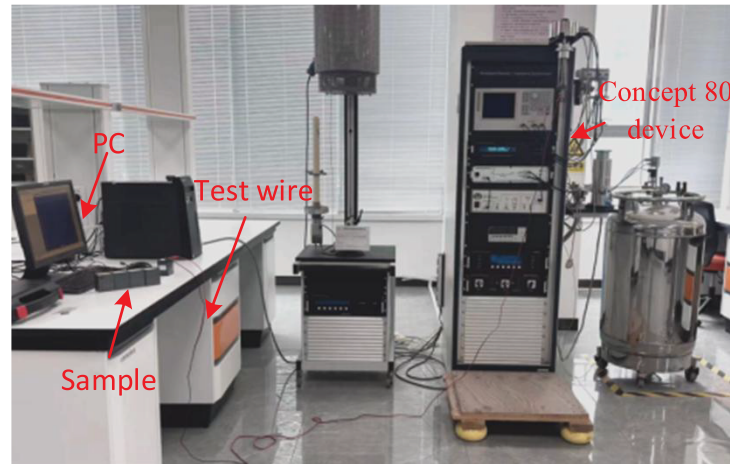


Figure 3: Testing experimental environment

2.3 Experimental Plan

According to T/ZAQ 10104-2022, the thermal aging treatment temperature for metallized film capacitors is specified to be between 20°C and 200°C. In this experiment, 16 samples were divided into four groups, with four samples in each group placed in the aging chamber. The temperature was set between 20°C and 120°C for accelerated aging, and the average value of each group of samples was selected as the experimental data. The aging time lasted for a total of 1080 h (45 days). Dielectric properties and capacitance deviations of each group of capacitors were measured in real-time at the time points of 0 h (no aging), 360, 720, and 1080 h using the spectrometer. The final average values were used for data analysis.

The detailed experimental conditions are as follows: The FDS measurements were conducted using an AC excitation voltage amplitude of 1 V RMS, with a measurement duration of 10 cycles at each frequency point to ensure signal stability. Prior to each measurement, capacitor samples were stabilized at room temperature ($25 \pm 2^\circ\text{C}$) for 30 min after removal from the aging chamber [31]. All measurements were performed at ambient temperature with relative humidity controlled at 45%–55%. The electrode connection employed a four-terminal configuration to minimize contact resistance effects. The thermal aging chamber provides temperature uniformity within $\pm 1^\circ\text{C}$ across the chamber volume, with temperature stability of $\pm 0.5^\circ\text{C}$ during continuous operation. The aging process was conducted in an ambient air atmosphere without protective gas, simulating realistic operating conditions for automotive applications. All 16 capacitor samples were from the same manufacturing batch (Lot No. 2024-Q3-0847) to minimize inter-sample variability. The measurement uncertainty was estimated at $\pm 2\%$ for capacitance and $\pm 3\%$ for $\tan \delta$ values based on repeated measurements of reference samples.

3 Experimental Results and Analysis

3.1 Capacitance Variation Analysis

Fig. 4 shows the schematic diagram of the equivalent circuit for the metallized film capacitor unit, where capacitors C_{n1} and C_{n2} are connected in parallel to form the basic unit module of the capacitor C in the circuit. R_p represents the insulation resistance of the organic film, R_s is the resistance of the conductive part, which includes the resistance of the gold spray layer, the resistance between the gold

spray layer and the metal portion of the film, the axial resistance of the metal on the film, and the resistance of the connecting wires. R_m represents the transverse resistance of the metal on the film.

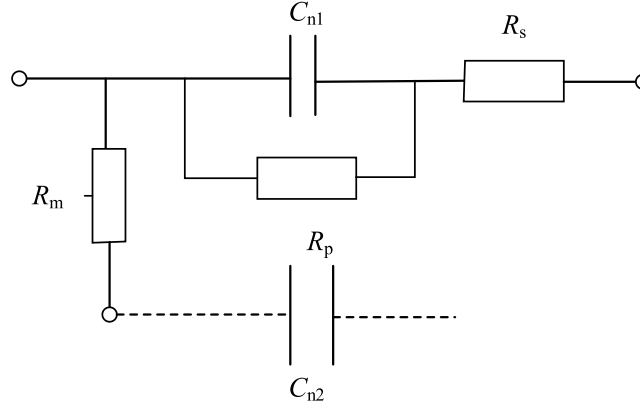


Figure 4: Schematic diagram of the equivalent circuit for the metallized film capacitor unit

Using the testing equipment, the capacitance characteristics of the capacitors at 0, 360, 720, and 1080 h after accelerated thermal stress aging were first measured and calculated. The capacitance of the metallized film capacitor can be calculated using the parallel plate model, based on the electrode area A and thickness d , with the following expression:

$$C = \frac{\varepsilon_0 \varepsilon_s A}{d} = \frac{\varepsilon_0 \varepsilon_s L f}{d} \quad (5)$$

where, ε_0 and ε_r represent the dielectric constant of vacuum and the relative dielectric constant of polypropylene film, respectively; L, f , and d represent the winding length, width, and thickness of the polypropylene film, respectively.

Fig. 5 shows the capacitance variation curves of MFCs at different aging times. First, it can be seen that the capacitance of each group of capacitors remains essentially unchanged across the frequency range from 50 Hz to 12 kHz. At 50 Hz, the capacitance values of the capacitors after different accelerated thermal aging times (0, 360, 720, and 1080 h) show a significant decrease, with values of 100, 99.3, 97.5, and 95.0 μF , respectively. The tolerances are 0.7%, 2.5%, and 5%, respectively. Notably, after 1080 h of accelerated thermal aging, the tolerance of the metallized film capacitors reaches 5%, indicating that the capacitor's lifetime is approaching the critical value. The rate of capacitance decay increases with aging time. As shown in the experimental data, the tolerance change from 0 h to the early stage of accelerated thermal aging (0–360 h) is 0.7%, with a stage change of $\Delta = 0.7\%$. In the middle stage (360–720 h), the change increases to 2.5%, with a stage change of $\Delta = 2.2\%$. In the late stage (720–1080 h), the change rapidly reaches 5.0%, with a stage change of $\Delta = 2.5\%$.

From Eq. (5), it can be observed that the capacitance value of metallized film capacitors is proportional to the dielectric constant of the film, winding length, width, and effective area, and inversely proportional to the film thickness. Therefore, the decrease in the capacitance of metallized film capacitors after thermal aging is mainly due to: (1) the accelerated oxidation and diffusion migration of the electrode metal in high-temperature environments, which also leads to a reduction in the dielectric breakdown strength; (2) local defects in the dielectric film, which are more likely to cause self-healing phenomena that create insulating isolation areas; (3) cracks in the metal layer of

the gold-sprayed layer, which reduce the effective area of the film, and the arcs generated during self-healing lead to the carbonization of the dielectric material, decreasing the local dielectric constant.

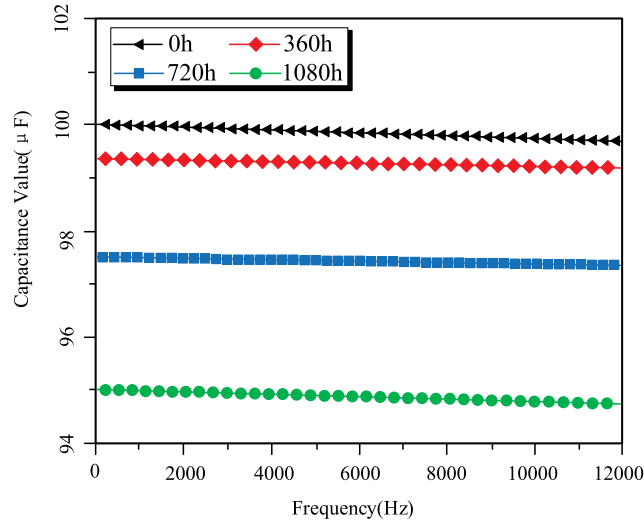


Figure 5: Normalized capacitance variation plot at different aging times

3.2 Dielectric Loss Analysis

In the assessment of the thermal aging state of MFCs, the change in capacitance reflects the overall degradation trend of the capacitor. However, its sensitivity to early-stage aging is low, and the numerical changes are not easily detectable. To gain a deeper understanding of the degradation process of the internal dielectric material in MFCs under thermal stress, it is necessary to analyze from the perspective of microscopic dielectric characteristics. The loss $\tan \delta$, as a comprehensive parameter representing both dielectric polarization loss and conductive loss, has higher sensitivity to changes in the material's microstructure. This section discusses the evolution of dielectric loss during the thermal aging process by analyzing the frequency-domain dielectric spectroscopy characteristics at different aging stages, exploring the intrinsic relationship between dielectric loss evolution and capacitance change, and providing experimental evidence for establishing an early warning method based on spectral features.

Fig. 6 shows the comprehensive relationship between frequency, dielectric loss tangent, and capacitance at different aging stages of MFCs. Figure a illustrates the variation of capacitance with frequency in the unaged state (0 h), and Figure b shows the variation of the dielectric loss $\tan \delta$ with frequency for the metallized film capacitors without accelerated thermal aging treatment. The nominal capacitance value of the tested samples is $100 \mu\text{F}$, and the initial capacitance loss is 0%. At the lowest test frequency of 50 Hz, the reference value of the dielectric loss tangent $\tan \delta$ is 2.21×10^{-2} , which will be used as the comparison baseline for subsequent accelerated thermal aging experiments.

Frequency-domain analysis results show that the dielectric loss tangent of the metallized film capacitors exhibits typical relaxation characteristics across the entire test frequency range: in the low-frequency range (50 Hz–1 kHz), $\tan \delta$ remains relatively low and increases slowly; in the mid-frequency range (1–10 kHz), $\tan \delta$ increases rapidly and peaks at 8100 Hz at 7.31×10^{-2} ; in the high-frequency range (≥ 12 kHz), $\tan \delta$ gradually decreases. This “increase then decrease” frequency dependence

reflects the relaxation loss mechanism of the polypropylene dielectric material, with the relaxation peak at 8100 Hz serving as the characteristic frequency for future aging state monitoring.

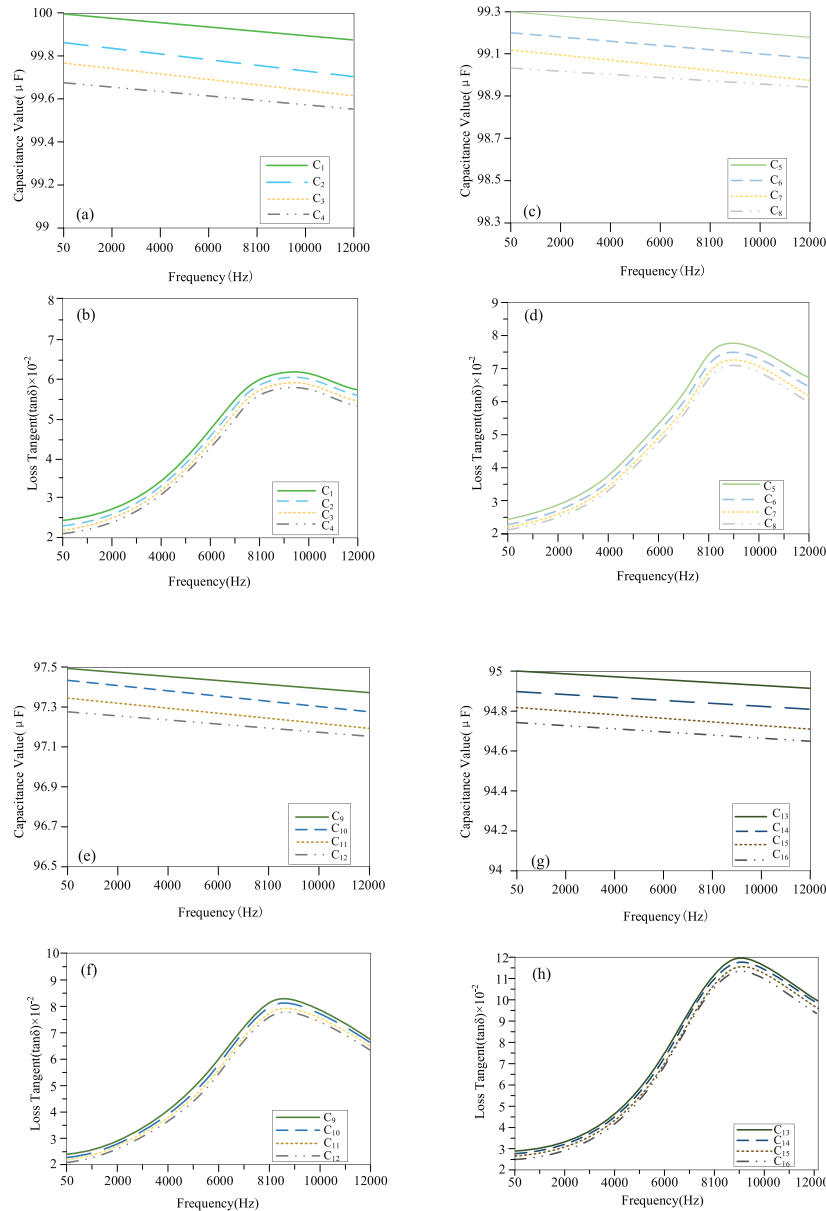


Figure 6: Frequency-dependent characteristics of capacitance and dielectric loss tangent ($\tan \delta$) at different aging stages of metallized film capacitors: (a) Capacitance variation with frequency at unaged state (0 h); (b) Dielectric loss tangent variation with frequency at unaged state (0 h); (c) Capacitance variation with frequency after 360 h thermal aging; (d) Dielectric loss tangent variation with frequency after 360 h thermal aging; (e) Capacitance variation with frequency after 720 h thermal aging; (f) Dielectric loss tangent variation with frequency after 720 h thermal aging; (g) Capacitance variation with frequency after 1080 h thermal aging; (h) Dielectric loss tangent variation with frequency after 1080 h thermal aging

Fig. 6c shows the capacitance variation with frequency after 360 h of accelerated thermal aging, and Fig. 6d shows the change in dielectric properties of the metallized film capacitor after 360 h of accelerated thermal aging. At this stage, the capacitance loss is only 0.7%, which is considered a minor change in conventional monitoring methods. However, frequency-domain dielectric spectroscopy analysis reveals more sensitive aging characteristics: at the characteristic frequency of 8100 Hz, the dielectric loss tangent $\tan \delta$ increases from 7.31×10^{-2} in the unaged state to 8.31×10^{-2} , a relative increase of 13.68%, significantly higher than the capacitance loss change. Across the entire test frequency range, $\tan \delta$ shows varying degrees of increase, but the frequency dependence retains the same relaxation characteristic as in the unaged state, with an “increase then decrease” trend in the low, mid, and high-frequency ranges.

Comparative analysis shows that frequency-domain dielectric spectroscopy technology offers significantly higher sensitivity for detecting early aging states of capacitors than traditional capacitance loss monitoring methods. When the capacitance loss changes by only 0.7%, the change in $\tan \delta$ at the characteristic frequency has already reached 13.68%, providing a more reliable basis for early aging warnings. Based on the dielectric loss spectrum feature analysis, it can be confirmed that the capacitor has entered the early stage of thermal aging.

Fig. 6e shows the capacitance variation with frequency after 720 h of accelerated thermal aging, and Fig. 6f shows the change in dielectric properties of the metallized film capacitor after 720 h of accelerated thermal aging. At this stage, the capacitor exhibits noticeable physical changes, with slight bulging, indicating significant internal structural changes. The capacitance test shows that the capacitance loss has increased to 2.5%, compared to the 360-h aging stage.

Frequency-domain dielectric spectroscopy analysis reveals more significant degradation information: at the characteristic frequency of 8100 Hz, the dielectric loss tangent $\tan \delta$ reaches 9.32×10^{-2} , an increase of 27.5% compared to the unaged state, and a further increase of 13.82% compared to the 360-h aging stage. Across the entire test frequency range, $\tan \delta$ values rise consistently, but the typical relaxation frequency dependence is maintained, showing an “increase then decrease” trend. Combined with physical appearance changes and the evolution of dielectric characteristics, it can be confirmed that the capacitor has entered the mid-stage of thermal aging.

Fig. 6g shows the capacitance variation with frequency after 1080 h of accelerated thermal aging, and Fig. 6h shows the change in dielectric properties of the metallized film capacitor after 1080 h of accelerated thermal aging. After 1080 h of aging, the capacitor shows severe bulging and cracking, and the capacitance loss reaches the 5% failure threshold. The results from Fig. 6h show that at the characteristic frequency of 8100 Hz, $\tan \delta$ reaches 11.37×10^{-2} , an increase of 55.5% compared to the unaged state. The test data indicate that when traditional capacitance loss monitoring reaches the 5% failure threshold, the change in the frequency-domain dielectric spectroscopy feature parameters exceeds 50%, verifying that FDS technology is 3–8 times more sensitive than traditional detection methods.

3.3 Mechanism Analysis

3.3.1 Frequency Band Layered Degradation Mechanism

As shown in Fig. 7, in the low-frequency range, due to the slower rate of change in the electric field, sufficient time is given for charges to redistribute at the interface, forming an interfacial dipole moment. This leads to the migration rate of interfacial charges lagging behind the low-frequency electric field changes, causing an increase in the imaginary part of the dielectric constant and a gradual

rise in the dielectric loss $\tan \delta$. At this point, dielectric loss is mainly caused by weak leakage currents induced by interfacial charge migration, with conductive loss becoming the dominant mechanism.

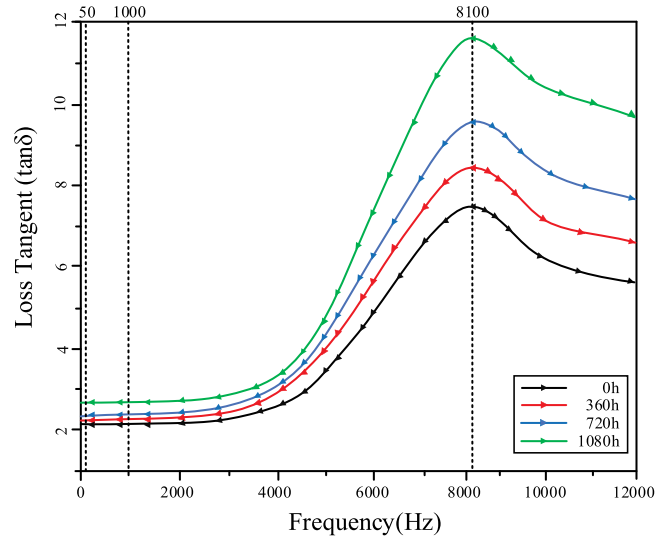


Figure 7: Normalized relationship plot between thermal aging frequency and dielectric loss tangent

As the frequency increases, in the mid-frequency range, the $\tan \delta$ value rapidly increases, reaching a relaxation peak at 8100 Hz, and then decreases. At this point, dielectric loss is influenced by the gradually shortened electric field change period, and the polarization of the dipoles lags noticeably behind the electric field changes. Relaxation polarization cannot fully establish, causing a decrease in the real part of the dielectric constant and an increase in $\tan \delta$ until the relaxation peak appears. This phenomenon is governed by both conductive loss and relaxation loss, but conductive loss decreases relative to its contribution as the frequency increases, since charge carriers cannot fully follow the electric field changes, reducing the conduction current. When the frequency of the electric field change approaches the characteristic frequency of the β relaxation process inside the dielectric, the polarization lag effect becomes most significant, and the energy loss reaches its maximum.

In the high-frequency range, $\tan \delta$ begins to decrease, mainly due to the failure of polarization. Slow-response processes such as interfacial polarization and dipole orientation polarization can no longer follow the high-frequency electric field changes and fail completely, leaving only fast-response mechanisms such as electronic polarization and ionic polarization to follow the electric field changes. Meanwhile, both relaxation loss and conductive loss decrease, leading to a reduction in overall dielectric loss. Furthermore, as the slow-response polarization processes fail, the effective dielectric constant decreases, and the capacitance correspondingly drops, which is consistent with the trend in $\tan \delta$ from a physical mechanism perspective.

3.3.2 Thermal Degradation Mechanism

During the early stage of thermal degradation (360 h). As shown in Fig. 8, during the low-frequency range (50–1000 Hz) of thermal aging, the high-temperature environment promotes the growth of internal dielectric defects and ion migration, increasing the charge trap density at the interface. During the redistribution of interface charges, more trap states participate in charge

migration, leading to an increase in the weak leakage current caused by interface charge migration, which in turn increases conductive loss.

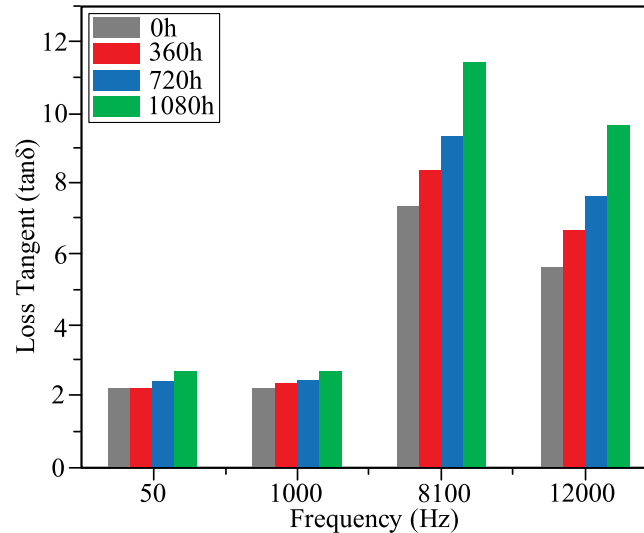


Figure 8: Normalized thermal aging time characteristic frequency histogram

In the mid-frequency range (1–10 kHz), thermal aging alters the dielectric structure, impeding the formation of interfacial dipole moments and increasing energy dissipation during relaxation. The combined effect of conductive and relaxation losses elevates the overall $\tan \delta$, with the relaxation peak at 8100 Hz rising from 7.31 to 8.31—a 12.1% increase. The unchanged peak frequency indicates that the dominant relaxation process remains consistent, while the increased amplitude points to a significant intensification of relaxation loss. This enhancement is attributed to the generation of structural inhomogeneities, such as defects and traps, within the dielectric material under thermal stress [32]. According to space charge accumulation theory [33] and the defect–polarization coupling mechanism [34], these thermally induced defects act as charge trapping sites that strengthen interfacial polarization and introduce additional relaxation processes. The resulting defect-related losses contribute prominently near the characteristic frequency, thereby raising the $\tan \delta$ peak.

During the mid-stage of thermal degradation (720 h), compared to the 360 h-aged sample, $\tan \delta$ continues to increase across all frequency ranges. In the low-frequency region, prolonged thermal stress and incipient partial discharge phenomena further elevate leakage current and conductive loss. Within the mid-frequency range, $\tan \delta$ rises sharply, with the peak at 8100 Hz reaching a value 21% above that of the unaged state—a greater increase than observed between 0 and 360 h, indicating accelerated deterioration of relaxation loss. Extended thermal aging promotes the degradation of polymer chains and oxidation reactions, generating additional polar groups and defects. These defects introduce further relaxation and structural defect losses near the characteristic frequency. As the electric field frequency approaches the defect relaxation frequency, polarization lag is enhanced, leading to higher energy loss.

Finally, during the late stage of thermal degradation (1080 h), At this stage, the capacitor experiences cumulative conductive and relaxation losses from earlier aging phases, along with more severe degradation due to prolonged high-temperature exposure. Accelerated oxidation of the aluminum and zinc electrodes occurs, as described by the following equations:



Existing studies have verified the aforementioned degradation mechanisms through material characterization techniques such as scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR). Reference [35] used SEM to observe the microstructure of metallized electrodes after thermal aging and found that under thermal stress of 120°C, an oxide layer approximately 50–80 nm thick formed on the surface of the aluminum electrodes and grew exponentially with aging time.

The thickness of the oxide layer produced by these oxidation reactions increases significantly, greatly reducing the effective area of the electrodes, as shown in Fig. 9.

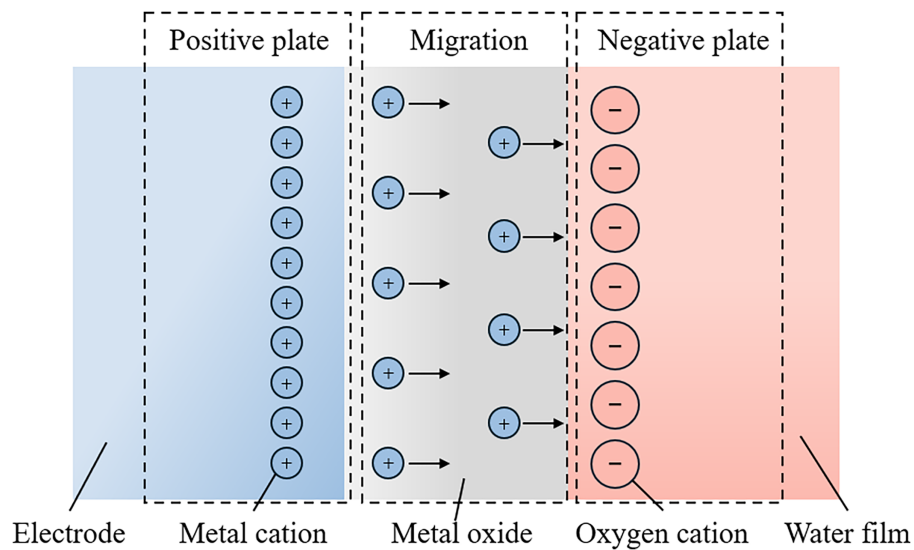


Figure 9: Double layer model of metallized electrode film degradation

At the same time, under the effect of thermal expansion, the internal volume of the capacitor expands, leading to severe bulging and cracking, which in turn damages the internal structure and triggers significant partial discharge. This partial discharge phenomenon further accelerates the carbonization of the capacitor, forming new conductive paths, which not only affects the capacitor's normal self-healing function but also intensifies capacitor breakdown. Additionally, it increases both conductive loss and polarization loss, further deteriorating the dielectric performance of the capacitor.

The dielectric loss mechanisms of capacitor thermal degradation are shown in Table 2:

Table 2: Thermal degradation dielectric loss mechanism

Mechanism	Generation principle
Conductive loss	Caused by dielectric leakage current and ion migration
Interfacial Polarization Loss	Interface charge accumulation forms reverse dipole
Dipole Polarization Loss	moment, extending the relaxation process

(Continued)

Table 2 (continued)

Mechanism	Generation principle
Space charge polarization loss	Oxidation in polypropylene generates polar groups, leading to lag in their orientation under alternating electric fields
Electrode polarization loss	Impurity ions accumulate in traps, hindering migration
Structural defect loss	Metal electrode oxidation increases contact resistance
Dimensions	Thermal stress leads to micro holes, cracks, or delamination within the dielectric, causing local electric field distortion

3.4 Quantitative Evaluation Method Based on Multi-Spectral Features

3.4.1 Principles of the Improved Weighted Fusion Algorithm

Traditional single weighting methods have obvious limitations: the Entropy Weight Method (EWM) relies entirely on objective data distribution and ignores expert knowledge, while the Analytic Hierarchy Process (AHP) overly depends on subjective judgment and is susceptible to human factors [36]. For the lifetime assessment of MFCs after thermal aging, although traditional detection methods provide intuitive data, they suffer from low sensitivity and difficulties in early aging state warning. Based on the FDS testing data already measured, this paper proposes a multi-spectral feature fusion evaluation method combined with an improved weighted fusion algorithm model [37,38], achieving quantitative assessment of MFC health status and lifetime prediction [39]. Table 3 presents a comparative analysis between the proposed improved algorithm and the traditional entropy weight method and AHP. The algorithm process is shown in Fig. 10. The Comparative Analysis is shown in Table 3:

Table 3: Comparative analysis of weighting methods

Method	Advantages	Disadvantages	Improvement in this paper
EWM	Strong objectivity, based on data distribution	Ignores expert knowledge, sensitive to outliers	Retains objectivity while reducing outlier impact through combination
AHP	Integrates expert experience, clear hierarchy	Strong subjectivity, difficult consistency verification	Uses three-scale method to improve consistency
Proposed	Adaptive subjective-objective integration	Slightly increased computational complexity	Achieves optimal fusion through iterative optimization

Based on the previous experimental analysis, construct a 6-dimensional feature vector to characterize the aging state of the capacitor [40].

$$X = [f_1, f_2, f_3, f_4, f_5, f_6]^T \quad (8)$$

where, f_1 is the $\tan \delta$ value at the characteristic frequency of 8100 Hz; f_2 is the frequency domain gradient; f_3 is the capacitance tolerance $\Delta C\%$; f_4 is the total frequency range loss integral; f_5 is the relaxation peak frequency shift; and f_6 is the spectral shape factor [41].

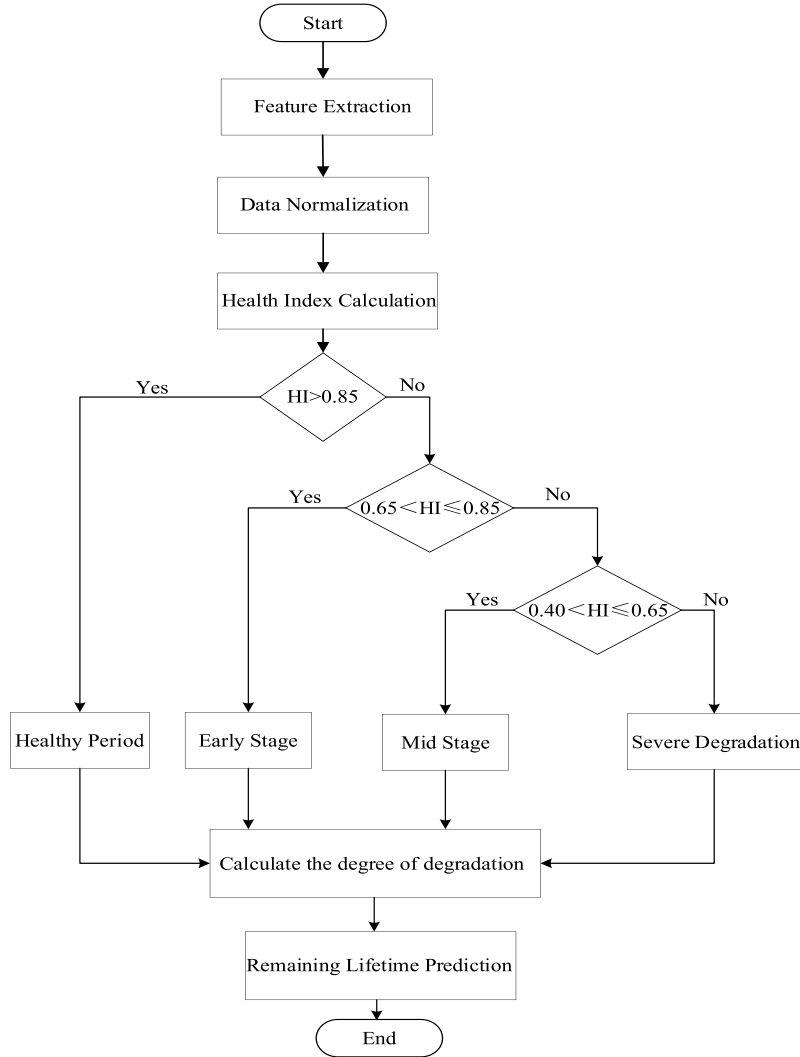


Figure 10: Intelligent assessment algorithm flowchart for MFC aging state

The HI is established using the improved weighted fusion algorithm:

$$HI = 1 - \sum_{i=1}^6 \omega_i \cdot f_i \quad (9)$$

where, f_i represents the normalized characteristic parameters.

$$f_i = 1 - \frac{f_i - f_{i_{\max}}}{f_{i_{\max}} - f_{i_{\min}}} \quad (10)$$

where, ω_i is the feature weight coefficient.

Based on the HI, a four-level aging state classification standard is established, as shown in [Table 4](#):

Table 4: State classification table

Aging stage	HI Range	Degradation degree (D)	State description
Healthy period	$HI > 0.85$	$D < 0.15$	Good performance
Early stage	$0.65 < HI \leq 0.85$	$0.15 \leq D < 0.35$	Slight degradation
Mid stage	$0.40 < HI \leq 0.65$	$0.35 \leq D < 0.60$	Significant aging
Late stage	$HI \leq 0.40$	$D \geq 0.60$	Approaching failure

The degradation degree D is defined as:

$$D = 1 - HI \quad (11)$$

Based on Weibull reliability theory and considering the aging acceleration effect [42], a Remaining Useful Life (RUL) prediction model is established:

$$RUL = \frac{HI - HI_m}{v_d \cdot (1 + \alpha (1 - HI))} \quad (12)$$

where, $HI_m = 0.40$ is the failure threshold; v_d is the current degradation rate; and α is the acceleration factor coefficient, with an experimental fitted value of 0.5 [43].

The experimental data from this study were substituted into the algorithm for validation, and the results are shown in [Table 5](#) [44].

Table 5: Result validation table

Aging time	Measured capacitance loss	Calculated HI	Determined stage	Predicted RUL (h)	Actual remaining (h)	Error
360 h	0.7%	0.78	Early stage	680	720	5.6%
720 h	2.5%	0.52	Mid stage	340	360	5.3%
1080 h	5.0%	0.38	Late stage	<20	0	0

3.4.2 Model Sensitivity Analysis

To evaluate the robustness of the HI model, sensitivity analysis was performed on each feature parameter. The Morris method was used to calculate sensitivity indices m^* and K for each parameter [45]:

$$m_j^* = (1/r) * \sum (|E_j|) \quad (13)$$

$$K_j = \sqrt{\left[(1/r) * \sum \left((E_j - m_j)^2 \right) \right]} \quad (14)$$

where, E_j is the elementary effect of the j-th parameter at the i-th sampling, and r is the number of samples. m^* reflects the overall influence of the parameter on model output, while K reflects the interaction strength between the parameter and other parameters.

The sensitivity analysis results are shown in Table 6. Results indicate that f_1 at 8100 Hz has the greatest influence on HI, $m^* = 0.423$, followed by f_3 , $m^* = 0.287$ and f_5 , $m^* = 0.156$. This validates the rationality of selecting 8100 Hz as the characteristic frequency.

Table 6: Sensitivity analysis results of feature parameters

Feature parameter	m^*	K	Sensitivity ranking
f_1	0.423	0.089	1
f_2	0.098	0.034	5
f_3	0.287	0.067	2
f_4	0.076	0.028	6
f_5	0.156	0.051	3
f_6	0.112	0.042	4

Additionally, perturbation analysis of the weight coefficient alpha shows that when alpha varies within $\pm 10\%$, the HI prediction error changes by no more than 2.1%, indicating good robustness of the model to weight parameters.

4 Conclusion

This study conducts an in-depth investigation into the dielectric loss characteristics of MFCs during the thermal stress aging process and compares the limitations of traditional loss detection methods using FDS technology. The results show that FDS technology has a significant advantage in early aging detection of capacitors, exhibiting high detection sensitivity and stability at the 8100 Hz characteristic frequency. Through a 120°C accelerated thermal aging experiment, a new MFC aging state assessment method based on $\tan \delta$ spectral features was successfully established. The main conclusions are as follows:

- (1) FDS offers significant advantages over traditional capacitance loss detection methods for early aging detection in MFCs. The comparison of ΔC and $\tan \delta$ across different aging stages shows that FDS can detect early degradation before traditional methods. Even with minimal changes in capacitance (such as a 0.7% change), FDS identifies significant increases in $\tan \delta$ at the characteristic frequency of 8100 Hz, providing a reliable early warning long before the capacitor reaches failure criteria. This demonstrates FDS's sensitivity, being 3–8 times more sensitive than conventional methods, and its potential for proactive maintenance.
- (2) This study identifies 8100 Hz as the characteristic frequency for MFCs, which exhibits a stable and distinct relaxation peak throughout the aging process. The amplitude of this peak increases significantly with the degree of thermal aging, making it a reliable indicator for assessing capacitor health. The characteristic frequency remains consistent, but the relaxation loss grows more pronounced as aging progresses, confirming its importance for early-stage monitoring and enabling more accurate predictions of capacitor performance.
- (3) A multi-spectral feature fusion HI model was established for the quantitative assessment of MFCs' aging states and the prediction of their RUL. By integrating features like $\tan \delta$ at the characteristic frequency, capacitance loss, and relaxation peak shifts, the HI provides a comprehensive evaluation of aging. The model, combined with Weibull reliability theory, offers highly accurate predictions, with an error margin of just 5.6%, even in the early stages of aging.

This method can be used to effectively monitor MFCs' condition, guide maintenance decisions, and ensure the reliability of systems using MFCs, particularly in electric vehicles.

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