Research Progress on Aging of Insulation Materials of Power Equipment under Extreme Temperature Cycles

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Abstract. Extreme temperature cycles critically threaten electrical insulating materials through thermal stress, oxidation, hydrolysis, and multi-field coupling effects, accelerating degradation via microcrack propagation and interface damage. While standardized tests (e.g., IEC 60216) assess thermal aging, they inadequately replicate multi-field coupling, risking distorted failure modes. Emerging online monitoring tools like terahertz time-domain spectroscopy (THz-TDS) and fiber Bragg grating (FBG) enable real-time defect imaging and strain-temperature tracking, enhancing condition assessment. Advanced lifespan models integrating multi-physics simulations and dynamic Bayesian networks outperform conventional methods, significantly reducing prediction errors. Material enhancements include functionalized nanofillers (KH-550-treated Al_2O_3, polydopamine-coated BN) to boost thermal conductivity and interfacial stability, while structural strategies like functional gradient materials (FGM) mitigate stress concentration. Protective coatings (superhydrophobic layers, phase-change materials) further improve resilience. Future priorities involve AI-driven predictive models, dynamic covalent bond networks for self-healing, and wide-temperature composites to ensure reliability in next-generation power systems. These innovations aim to address aging mechanisms holistically, bridging gaps between accelerated testing and real-world performance under extreme thermal cycling.

Keywords: Extreme Temperature Cycling, Insulation Material Aging, Life Prediction, Accelerated Aging Test

1 Introduction

Power equipment insulation materials are prone to performance degradation or even failure due to thermal stress and material degradation under extreme temperature cycling conditions.

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In recent years, the frequent occurrence of extreme climate events has led to an increasingly harsh operating environment for power equipment. The global failure rate of power equipment caused by sudden temperature changes is increasing annually. For instance, a 220kV GIS terminal failure in China resulted from epoxy resin cracks induced by extreme temperature cycling. Existing insulating materials face significant performance degradation under wide temperature range (-40~120°C) cycles: epoxy resin produces microcracks due to thermal expansion coefficient mismatch, and silicone rubber loses its hydrophobicity due to thermal oxygen cross-linking, which seriously threatens equipment reliability. Developing insulation materials resistant to extreme temperature cycles has become a core requirement for ensuring the safe operation of new power systems.

Many studies have focused on material modification and structural optimization to address insulation aging issues at extreme temperatures in recent years. The main technical measures include: Nanofiller modification: Using KH-550 (f-AFs) to treat Al_2O_3 nanoparticles can reduce interfacial thermal stress mismatch, which not only improves the thermal conductivity of the material, but also has good dielectric properties and dielectric breakdown strength. BN nanoparticles improve interfacial compatibility through surface functionalization, thereby increasing the thermal conductivity of silicone rubber [1].

However, there are still many limitations. For example, most current studies focus only on thermal aging, while ignoring the electro-thermal-mechanical multi-field coupling effect. The equivalence of accelerated experiments is also questionable. The IEC 60216 standard is based on the linear extrapolation method of the Arrhenius model. In some accelerated aging experiments, better life predictions can be made by other methods rather than forced linear extrapolation [2]. At the same time, most of the resulting materials are not suitable for engineering applications, and laboratory-level material modifications (such as high-cost nanofillers) are difficult to apply to actual production on a large scale due to various factors. This paper aims to discuss the physical-chemical synergistic aging mechanism of insulating materials under extreme temperature cycles and establish a multi-field coupling life prediction model to guide actual production.

2 Insulation Aging Mechanisms

2.1 Comprehensive Aging Mechanisms

Physical Aging. Electrical insulation materials will physically age under long-term electric fields, temperature, and mechanical stress, resulting in a decrease in insulation performance or even loss of insulation ability.

Temperature increase can break the molecular chains of the materials, decrease the crystallinity, or destroy the cross-linking structure, thereby reducing their insulation strength. High temperature accelerates the motion of the molecules of the insulation materials, causing the material structure to fatigue and become brittle, resulting in a decrease in the insulation performance. For example, when hard epoxy resin is heated at 120°C, it becomes hard and brittle, and the complex permittivity increases [3].

UV light can cause polymer chain scission. The energy of ultraviolet light can break C-C bonds and C-H bonds, triggering a free radical chain reaction. Take cross-linked polyethylene (XLPE) cable sheath as an example, under the influence of temperature and ultraviolet light, there is a strong competition between oxidation and cross-linking, which causes the dielectric constant, dielectric loss factor, and dielectric loss index of XLPE to increase [4]. Similarly, ultraviolet radiation can also cause microcracks on the surface of the insulator shed [5].

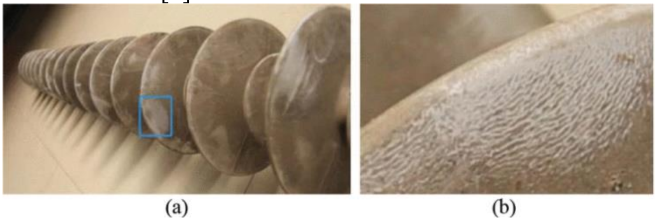

Fig. 1. Micro-cracks on an insulator [6]

Chemical Aging. Chemical aging is the process in which the physical and electrical properties of insulation materials gradually deteriorate due to chemical factors during long-term use.

When insulation materials are exposed to air, they can react with the oxygen in the air. Oxygen reacts with insulation materials, generating free radicals and triggering chain reactions, causing the material to become brittle and crack. There is a good correlation between the formation of oxidation products and the reduction of mechanical properties. For XLPE, material embrittlement occurs because of chain scission and chemical crystallization [7]. The results in the figure below illustrate the uneven oxidation of XLPE.

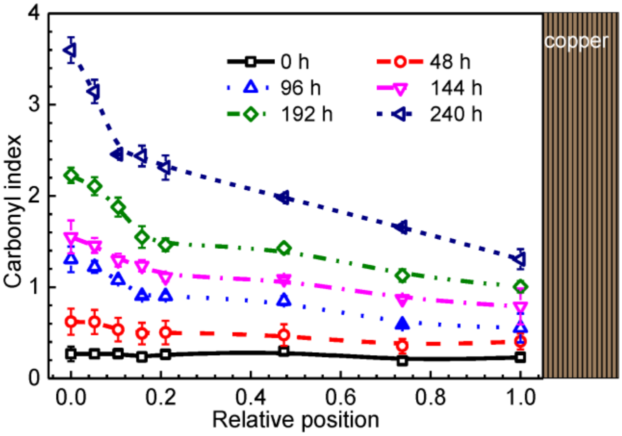

Fig. 2. Profile of carbonyl index for different XLPE samples [8]

Hydrolysis is one of the important types of chemical aging, which refers to the process in which water molecules break and reorganize the chemical bonds in the material. Hydrolysis can cause the polymer's main or side chain to break, generating small molecules. Water molecules attack polar chemical bonds in the insulation materials, breaking down the macromolecular chain into small molecular fragments through nucleophilic substitution or addition reactions, which can lead to material embrittlement.

Electrical Aging. Electrical aging refers to the process in which the electrical, mechanical, or chemical properties of a material gradually degrade under the action of a long-term electric field, eventually leading to insulation failure.

Tiny defects inside or on the surface of the material can cause intermittent discharges in areas where the electric field is concentrated; this phenomenon is called partial discharge. Partial discharge occurs when the electric field intensity exceeds a critical threshold, triggering a localized breakdown in the surrounding insulating medium [9]. Partial discharges can generate ozone (O_3) and nitrogen oxides (NOx), which can accelerate the oxidative decomposition of organic insulation materials.

Under high electric fields, defects inside the material induce dendritic conductive channels that extend from the electrode into the material, this process is called electrical treeing. This process can ultimately lead to a complete breakdown of the insulation, triggering equipment failure. It is essentially a destructive combination of electric field energy and material defects, commonly found in polymer insulations.

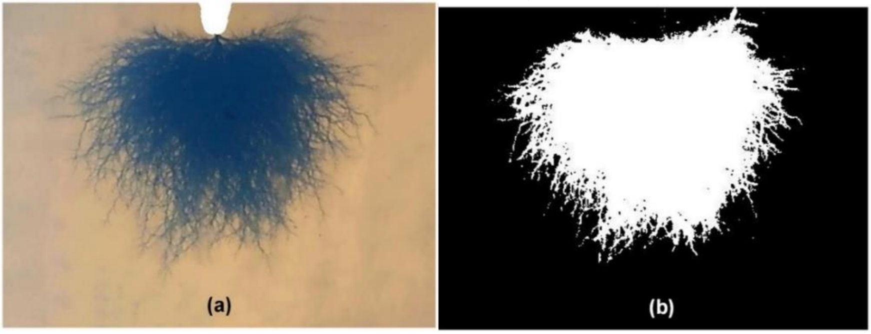

Fig. 3. A typical electrical tree [10]

2.2 Temperature Cycle Specific Mechanism

To improve the electrical properties of the material, the insulation material is usually not only a single component, but will be added some other components, used to improve the mechanical properties, heat resistance, thermal conductivity, or to reduce costs, or to improve the flexibility and processability of the material, and to ensure the stability of the material in the processing as well as the subsequent use of the process of the flame retardant requirements, the material will also be added with stabilizers and flame retardants. Therefore, insulation materials are usually composed of various components, and different materials have different coefficients of thermal expansion. Repeated expansion and contraction of the material during temperature cycling leads to the accumulation of internal stresses, which may trigger micro-cracks, delamination or interfacial debonding. Certain materials become brittle at low temperatures and soften at high temperatures. Repeated temperature changes can lead to fatigue fracture of the material, and ultimately to the formation of penetrating cracks. Cracks in the material can, in turn, lead to the onset of electrical aging. The pit in the figure below indicates that one of the components is debonded, indicating that the interface compatibility is poor, leading to stress concentration and thus the formation of cracks.

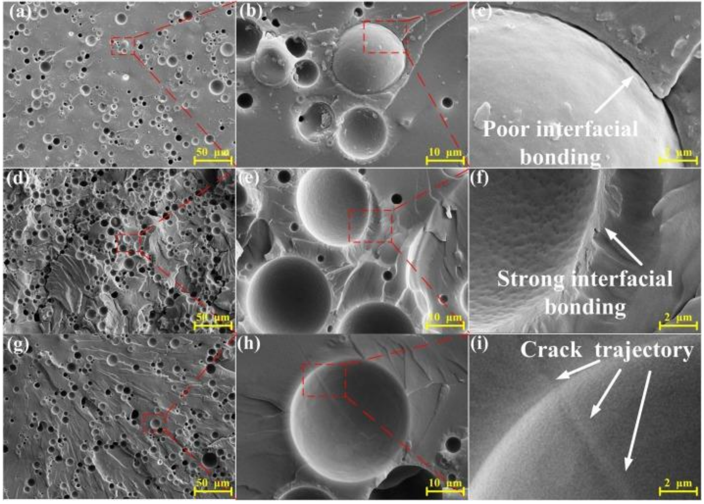

Fig. 4. Fracture surface of a composite material [11]

Semi-crystalline polymers may undergo a crystallization-melting process during temperature cycling, resulting in the destruction of the crystalline region and reduced mechanical strength and insulation performance. During the temperature cycle, the cooling stage may cause water to penetrate the material due to dew point condensation, triggering a hydrolysis reaction and destroying the polymer chain. The combined effect of water and an electric field can also cause partial discharge and form conductive dendritic channels.

3 Aging Experimental Methods

3.1 Accelerated Aging Test

The accelerated aging test of electrical insulation materials is an important method to evaluate their performance degradation under stresses such as high temperature, electric field, and humidity. It is used to predict the life and reliability of materials in actual use. In this essay, the thermal aging test is mainly discussed. The current mainstream test methods can be divided into the IEC 60216 series methods based on international standards and non-standard tests (such as the step temperature method). Significant differences exist between these two methods in test design, equivalence, and risk control.

IEC 60216-1:2013 standard employs the Arrhenius model to derive the relationship between material lifespan and temperature.

The Arrhenius model states that the rate of chemical reaction increases exponentially with increasing temperature. Because high temperature accelerates the breakage of molecular chains and oxidation reaction within the material, it also accelerates the polymerization and phase change of polymers, which leads to the degradation of material properties. The commonly used high temperature aging test method is to place the material into a high temperature aging test chamber, set a certain time and temperature, and observe the performance changes of the sample. This standard requires that no material phase change occurs within the test temperature range.

As for the non-standard tests, multiple temperature gradients can be set in the experiment, and the material's dielectric constant can be tested periodically, to draw the performance curve with temperature change. Non-standard tests, such as the step temperature rise method, accelerate aging by gradually increasing the temperature stress. Its advantage is that it shortens the test cycle. However, this method may cause the failure mode to be distorted due to "over-acceleration". For example, the step temperature rise method may cause the material to experience ultra-high temperature (such as >150°C) in a short time, causing a viscous flow transition or interface debonding that is inconsistent with the actual working conditions, causing the micro crack formation mechanism to deviate from the actual aging path. Studies have shown that, taking the elongation at break of XLPE as an example, the mechanical properties of XLPE drop to 235% when aged for 800 hours at 135°C. At a higher temperature of 150°C, simulating a cable short circuit, the insulation material will deteriorate significantly, from 560% to 37.5%. However, the actual operating temperature (90°C) only drops from 560% to 500%, indicating that high temperature acceleration may exaggerate the material embrittlement rate [12].

It is recommended to give priority to the IEC 60216 standard framework in the study of insulation material aging. If non-standard tests are required, the consistency of failure modes should be verified through microscopic characterization, and multi-model cross-validation should be used to reduce prediction errors.

3.2 Online Monitoring Technology

Online monitoring technology provides dynamic data support for aging assessment under extreme temperature cycles by sensing the performance degradation of insulating materials in real time. Among them, fiber Bragg grating (FBG) and terahertz time-domain spectroscopy (THz-TDS) are breakthrough technologies.

Fiber Bragg Grating (FBG) Temperature-strain Synchronous Monitoring. FBG can be embedded to monitor the internal state of insulating materials based on the sensitive characteristics of grating reflection wavelength to temperature and strain. For example, FBG sensors are implanted in high-voltage electrical equipment to detect partial discharge in high-voltage power transformers online. The modulated optical signal of the fiber-based sensor has only a small loss in long-distance transmission, and due to its dielectric properties, no additional insulation device is required when installed in the equipment. Experiments have shown that it can replace traditional partial discharge measurement systems [13]. Furthermore, multi-FBG arrays can construct distributed sensing networks to achieve more accurate monitoring.

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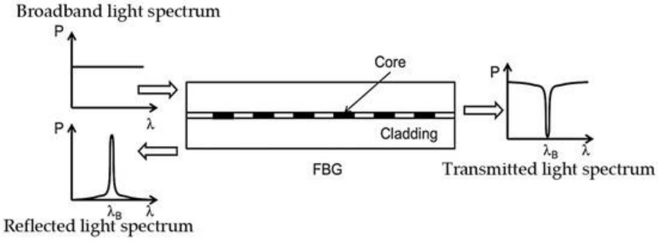


Fig. 5. The working principle of FBG [14]

Terahertz Time Domain Spectroscopy (THz-TDS) Nondestructive Testing. THz-TDS uses the strong penetration of terahertz waves into non-polar materials to achieve non-destructive imaging of internal defects in insulators. It has the characteristics of high resolution, non-destructiveness, and multi-parameter analysis. For some materials, sound waves decay very quickly, and general detection methods are ineffective. Terahertz detection is very suitable for the detection of these materials. Moreover, terahertz detection is simpler to operate than traditional ultrasonic detection, and imaging can be performed without contacting the surface of the object. At the same time, compared with X-ray digital imaging technology, it is also safer and has minimal radiation damage to the human body [15].

4 Aging Model and Life Prediction

4.1 Aging Model

The aging model is the core tool for predicting the life and degradation behavior of insulating materials. Its development process shifting from a single stress empirical model to a multi-field coupled intelligent model.

The Arrhenius model is a model for predicting thermal aging life based on temperature acceleration factors, and is suitable for constant temperature scenarios, such as the 90°C thermal oxygen life assessment of cable XLPE insulation. However, in high-temperature accelerated tests, phase changes, crosslinking/melting, or side reactions may occur in the material, resulting in aging mechanisms that are different from actual low-temperature use conditions. For example, the slow process that dominates at low temperatures cannot be accurately simulated by high-temperature acceleration, which may lead to inaccurate results.

The Eyring model introduces the coupling term of electric field intensity and temperature, which can describe the electric-thermal combined aging and is widely used in transformer oil-paper insulation life prediction. The Eyring model assumes that the reaction proceeds through a single transition state, but the actual aging may be in a non-equilibrium state, and the transition state theory is based on the equilibrium state assumption and is difficult to apply directly.

Through molecular dynamics simulation, the software builds models to reveal the chain segment mobility and interface debonding mechanism. For example, the periodic amorphous structure of cross-linked epoxy resin compounds is constructed to simulate the changes of cross-linked epoxy resin at different temperatures, and its glass transition temperature (Tg), linear thermal expansion coefficient, and Young's modulus are predicted. The results are in good agreement with the actual values [16].

Traditional models are usually limited, while emerging technologies provide high-precision analysis tools for multi-stress coupled aging through cross-scale modeling and data-driven optimization, but the balance between model generalization and computational cost still needs to be solved.

4.2 Lifespan Prediction Methods

Life prediction is an indispensable part of practical applications. Life prediction methods quantify the degradation process of insulating materials under extreme temperature cycles through mathematical models.

Weibull distribution has become a mainstream tool for reliability analysis due to its flexible shape parameters. Common insulation performance degradation usually follows a Weibull distribution, so the two-parameter model can describe the change of material failure probability over time.

For example, in the study of cable failure rate, the predicted results of this model are compared with the actual results, which shows that it has a certain degree of accuracy. However, in practice, multi-stress coupling leads to dynamic changes in failure thresholds, which significantly increase the complexity of the model [16]. Dynamic Bayesian networks (DBNs) that integrate multi-source data and online monitoring data can also be added to achieve dynamic life updates through probabilistic reasoning.

5 Methods to Improve the Anti-aging Properties of Insulation Materials

5.1 Material Modification

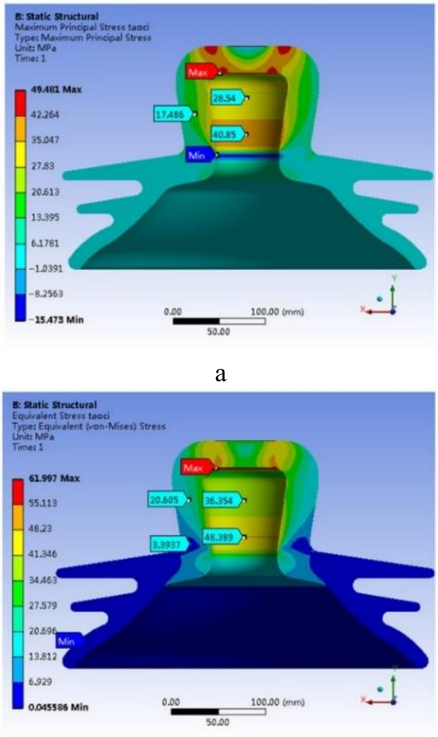
Material modification is the core strategy to improve the anti-aging performance of the insulation materials. Functionalized nanocomposites optimize the thermal-mechanical fatigue resistance and electrochemical stability of insulating materials, providing innovative solutions for extreme temperature scenarios.

Functionalized nanoparticles can enhance interfacial stability. Improving the dispersibility and interfacial compatibility of nanofillers through surface modification can significantly inhibit the propagation of microcracks under extreme temperature cycles. For example, Al_2O_3 nanoparticles were treated with KH-550 (f-AFs), and the amino functional groups grafted on their surfaces can form strong hydrogen bonds with the epoxy matrix, reducing the interfacial thermal stress mismatch. Studies have shown that when 50 vol% /-AFs are added, the thermal conductivity of the composite material is as high as 1.27 $W{\cdot}m^{-1}{\cdot}K^{-1}$, which is six times higher than the thermal conductivity of pure epoxy resin. In addition, this improvement is accompanied by good dielectric properties and dielectric breakdown strength compared with pure epoxy resin [17].

Hexagonal boron nitride (h-BN) has good thermal conductivity and insulation properties. Polydopamine (DA) is used to coat h-BN for bio-modification, which reduces the thermal resistance of h-BN in silicone rubber and improves the interface compatibility between h-BN and silicone rubber, thereby improving the thermal conductivity of silicone rubber. The lowest volume resistivity of the composite material is 30 wt% h-BN@PDA/silicone rubber, which still maintains 2.5 × 1011 Ω·cm, which means it still has good insulation properties [18].

5.2 Structural Optimization

Drastic temperature changes can cause shear stress inside the material due to differences in thermal expansion coefficients, which can eventually lead to microcracks. Structural optimization alleviates stress concentration under extreme temperature cycles through gradient design and improves the reliability of the insulation system. Taking the basin insulator of gas-insulated switchgear (GIS) as an example, the traditional equal thickness structure is prone to microcracks at the root of the stress cone due to mismatch of thermal expansion coefficients in temperature cycles with large temperature differences. The figure below shows the simulated stress distribution of two insulators with optimized structures. It can be seen that the internal stress distribution of the optimized insulator is more uniform.



a

b

Fig. 6. Simulated stress distribution diagram of two insulators [19]

By optimizing the geometric parameters of the stress cone through finite element analysis (FEA), such as increasing the cone angle and the root fillet radius, the uniformity of the electric field intensity distribution can be improved and the maximum thermomechanical stress can be reduced. Further adopting the functional gradient material (FGM) design, the Al_2O_3 filler is distributed along the radial gradient, which can not only reduce the negative impact on the elongation of the composite material but also improve the strength [20]. The gradient insulation design provides a low-stress, high-stability solution for extreme temperature scenarios through geometry-material synergy optimization.

5.3 Protective Measures

To address the damage to insulating materials caused by extreme temperature cycles, external protective measures can significantly improve material durability through physical isolation or active temperature control. Two technologies can be used, including super-hydrophobic coatings and intelligent thermal management.

The bionic lotus leaf structure super-hydrophobic coating locks the air layer through the micro-nano rough structure, reducing the surface moisture adsorption and partial discharge. For example, the SiO2/fluorocarbon resin composite coating is constructed on the surface of silicone rubber by the sol-gel method. Fluorocarbon resin is a commonly used topcoat material in the coating system. The SiO2-GO/FC composite coating prepared by modifying graphene oxide by the sol-gel method is characterized by the friction coefficient and wear rate under the 50-day long-term immersion test. An oxide layer is formed between the coating and the substrate. In addition, the maze effect formed by SiO2-GO inside the coating reduces corrosion damage [21].

Phase change materials (PCM) buffer sudden temperature changes by absorbing latent heat and reducing thermal stress of insulating materials. For example, paraffin wax/expanded graphite composite PCM can be encapsulated on the surface of GIS pot-type insulators. Because paraffin wax is a phase change material with low thermal conductivity, it is mixed with expanded graphite by melt blending and pressed into a shape-stable phase change material. After research, 10 wt% EG/PW CPCM can increase the thermal conductivity of paraffin wax from 0.2 W/(m·°C) to 7.06 W/(m·°C) [22]. In temperature cycles with large temperature differences, the temperature rise rate of internal insulating materials can be greatly reduced, thereby reducing the generation of microcracks in the insulating materials and playing a protective role. Furthermore, an active thermal management module based on shape memory alloy can also be used, which can adaptively adjust the heat dissipation area according to the temperature, adjust the temperature of the equipment within a certain heat load range, and the temperature overshoot is small (the maximum value is 16.8%). It plays a key role in providing robust thermal management performance [23].

6 Conclusion

Recent studies have shown that under extreme temperature cycles, the aging of insulating materials is dominated by interface damage, including mechanisms such as epoxy resin-filler interface debonding. Life prediction methods are transforming from empirical models, such as the Arrhenius model, to multi-physics field coupling models, such as dynamic Bayesian networks that combine electrical-thermal-mechanical stress fields, and the prediction error is significantly reduced. The use of online detection technology enables the state of insulating materials to be better monitored when used in actual engineering, which facilitates unified management. In addition, the engineering application of functional gradient materials (FGM) has improved the life of the insulation system under extreme temperature changes.

In a short time, develop wide-temperature composite insulating materials, focusing on breakthroughs in the directional arrangement of nanofillers and dynamic covalent bond networks, to maintain a high level of dielectric strength retention after multiple temperature cycles. In the long term, build a digital twin-driven insulation health management system, transmit multi-source monitoring data (FBG strain, THz-TDS defect imaging) through 5G, rely on edge computing to analyze the material degradation state in real time, and combine the molecular dynamics-machine learning hybrid model to achieve accurate prediction of material life. At the same time, cross-disciplinary integration, in the future, it is necessary to deepen the intersection of materials, information, and energy, establish a standardized multi-stress coupling aging database, and provide highly reliable insulation solutions for the healthy operation of new power systems.

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