Overview of the Aging Mechanisms and Diagnostic Methods of Oil-Immersed Transformer Insulation Systems

Ruiming Wang, Fubao Jin, Shangang Ma, Deibao Wang

***Abstract*—The aging of insulation in oil-immersed transformers is a critical factor influencing their operational performance and service life. This paper summarizes the mechanisms of thermal aging, electrical aging, oxidative aging, and hydrolytic aging of oil-paper insulating materials, while also discussing the relevant influencing factors. Various aging diagnostic techniques are introduced, including degree of polymerization measurement, moisture content detection, and dielectric response methods, with an evaluation of their basic principles and practical applications. In response to the challenges posed by insulation aging, this paper proposes several future research directions: advancing the development of novel insulating materials with enhanced aging resistance; designing high-precision online monitoring technologies for real-time condition assessment; leveraging big data and artificial intelligence to establish predictive aging models and enable intelligent maintenance; conducting in-depth studies on the microscopic mechanisms of insulation aging to support the evolution of diagnostic techniques; and refining detection standards to enhance accuracy and reliability.**

***Index Terms*—oil-immersed transformers, insulation aging, condition monitoring, intelligent maintenance**

I. Introduction

DRIVEN by the global "dual-carbon" initiative, the power systems is accelerating technological innovation and promoting the construction of smart grids, making transformer aging condition monitoring a key task. As the core hub of the power systems, large oil-immersed transformers bear the heavy responsibility of electricity conversion and distribution, and their insulation status directly affects the stability of the power grid and life security[1]. Statistics indicate that insulation failures account for up to 45% of transformer breakdowns with voltage levels of 110 kV and above, highlighting the urgent need to enhance insulation condition monitoring[2][3].

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According to the IEC 60076-1 standard, the typical service life of distribution transformers is approximately 20 years under standard operating conditions, while that of power transformers is around 30 years[4]. However, the actual lifespan is significantly influenced by environmental factors such as ambient temperature, humidity, electrical stress, and mechanical vibrations [5]. Current research has confirmed that the aging of oil-paper insulation systems results from a combination of thermal, electrical, chemical, and mechanical stresses. Therefore, it is essential to carry out more comprehensive and in-depth study on the aging mechanisms of oil-immersed transformer insulation systems and their associated diagnostic methods.

Currently, diagnostic techniques involve analyzing the dissolved gas content in oil, measuring furfural concentration, and assessing the Degree of Polymerization (DP) of insulation paper. Additionally, advanced diagnostic methods such as frequency-domain dielectric response and space charge distribution curves are widely utilized. To further enhance the accuracy and intelligence of monitoring systems, intelligent algorithms—such as Genetic Algorithms (GA) and particle swarm optimization (PSO)[6]-[9]. However, most existing studies rely on a limited set of characteristic parameters to monitor transformer aging, which leads to inaccuracies and limitations in reflecting the comprehensive aging status. Integrating electrical characteristic parameters with physicochemical characteristic parameters can significantly enhance both the efficiency and accuracy of transformer aging assessments.

This paper begins by summarizing the current research status of insulating oils utilized in oil-immersed transformers, highlighting the respective advantages and limitations of mineral-based and vegetable-based insulating oils. It then delves into the aging products and evolution patterns of commonly used mineral insulating oils and cellulose insulating papers, providing an in-depth analysis of the aging mechanisms within oil-immersed transformer insulation systems. Finally, the paper reviews existing assessment methods for evaluating the aging states of both insulating oils and oil-paper insulation, emphasizes potential future research directions, and aims to provide both theoretical support and practical guidance for related scientific and engineering endeavors.

II. Performance Characteristics and Aging Mechanisms of Insulating Oil

A. Key Performance Characteristics of Insulating Oil

As the core medium within transformers, insulating oil performs several critical functions, including electrical insulation, cooling, and arc suppression. Its essential properties—such as oxidation stability, high dielectric strength, thermal stability, flame retardancy, and low-temperature fluidity—directly impact the operational safety and service life of the equipment[10].

The chemical composition of various insulating oils significantly influences their electrical performance and aging characteristics. In recent years, vegetable insulating oils have emerged as promising alternatives due to their renewable nature, high biodegradability, and favorable dielectric properties. Compared to mineral insulating oils, they provide superior thermal resistance and enhanced environmental sustainability. However, the technology surrounding vegetable insulating oils remains underdeveloped, and their practical applications are constrained by drawbacks such as high viscosity, and poor oxidation stability. Consequently, mineral insulating oils continue to dominate the market due to their stability and cost-effectiveness, which hinders the widespread adoption of vegetable insulating oils in practical applications.[11]. Numerous researchers have conducted comparative studies between vegetable-based and mineral-based insulating oils[12]-[15]. The results indicate that in experiments involving partial discharge gas generation and multiphysics simulations, mineral insulating oil demonstrates superior heat transfer efficiency. In contrast, Reference [16] focuses on the dielectric loss factor and volume resistivity, revealing that nano-modified plant oil outperforms nano-modified mineral oil. Additionally, Reference [17] investigated the aging behavior of mixtures of plant oil and mineral oil at various ratios, analyzing their electrical properties and flow characteristics. The study concluded that blending the two oils at an optimal ratio can enhance the overall performance of the insulating oil.

In conclusion, further research is essential to improve the physicochemical properties of vegetable insulating oils and to lower production costs, thereby unlocking their full potential as high-performance insulating liquids. This paper primarily examines the aging characteristics of mineral insulating oils, which continue to be widely used in practice, with the objective of offering valuable references for research and applications in related fields.

B. Aging Mechanism of Mineral Insulating Oil

The chemical composition of mineral insulating oil in transformers primarily consists of aromatic hydrocarbons, cycloalkanes, alkanes, and other hydrocarbons, forming a complex mixture. Factors such as oxygen, temperature, and humidity influence multi-stage aging reactions, which are characterized by the coupling of multiple mechanisms, including oxidation, thermal cracking, and electrical aging. Each reaction product undergoes continuous transformation through secondary reactions, such as esterification, resulting in a dynamic and deteriorating cycle.

1) Thermal Degradation Mechanism

During the manufacturing, operation, and maintenance of transformers, the exposure of insulating oil to air allows oxygen to permeate through the oil-gas interface, initiating a thermal oxidation aging process. The chemical equation is depicted in Fig.1.

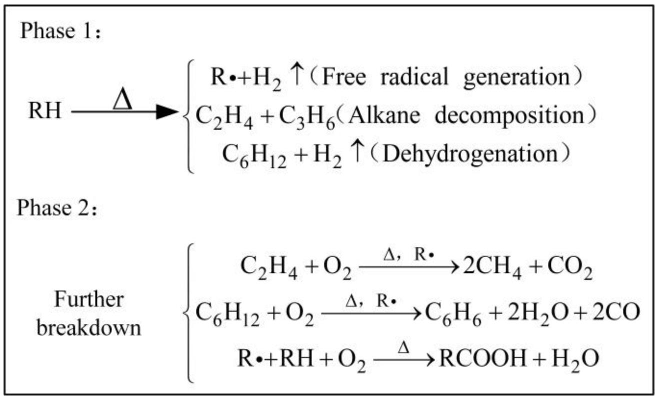

Fig. 1. Thermal-oxidative degradation of insulating oil

Reference [18] categorizes the thermal aging process of mineral insulating oil into two distinct stages. In the initial stage, the carbon–carbon bonds within alkane molecules cleave, resulting in the formation of olefins (e.g., ethylene and propylene), cycloalkanes (e.g., cyclohexane), and hydrogen. These smaller molecules subsequently undergo further degradation into gases such as CH_4, while cycloalkanes experience dehydrogenation aromatization. This sequence of reactions compromises the thermal stability of the insulating oil, and the degradation products can further accelerate the aging of the insulation paper [19]. Reference [20] conducted thermal aging experiments on insulating oils at temperatures ranging from 80°C to 140°C to evaluate their dielectric loss factor, acidity, and moisture content. This research ultimately established an exponential model to predict the aging of insulating oil, thereby providing a valuable reference for understanding the thermal aging process.

The CIGRE research group has systematically summarized the oxidation mechanisms and oxidative stability of insulating oil[21]. In the initial stage of oxidation, oxygen reacts with unsaturated hydrocarbons, such as aromatic hydrocarbons and cycloalkanes, to form peroxide radicals that initiate a chain reaction. During the intermediate stage, the decomposition of peroxides generates low-molecular-weight organic acids, aldehydes, ketones, and hydrogen peroxide, significantly increasing the acid number and accelerating oil aging. As a potent oxidizing agent, hydrogen peroxide further catalyzes oxidative reactions, while the acidic byproducts corrode the metallic components of the equipment, releasing metal ions that promote sludge formation. As oxidation progresses, large quantities of end-products accumulate, leading to excessive acidity, increased dielectric loss, elevated moisture content, and ultimately, a decline in both insulation strength and thermal stability.

2) Electrical Aging Mechanism

Electro-aging is a multifactorial synergistic process involving electric fields, temperature, oxygen, and moisture, and is significantly more complex than thermo-oxidative aging. Under high-voltage electric field conditions, charge carriers in the oil migrate, forming current paths that trigger the thermal cracking of oil molecules. This process generates hydrogen, low-molecular-weight hydrocarbons, and carbonaceous particles. Simultaneously, reactive radicals produced by electrical discharges react with oxygen to form peroxides, which subsequently decompose into organic acids and water, initiating a vicious cycle of increasing acidity and sludge formation [22]. The American Society for Testing and Materials (ASTM) has proposed a standard method for evaluating the electrical aging of insulating oil, known as ASTM D80–2008 [23]. Based on this standard, Reference [13] conducted electrical aging experiments on various insulating oils and found that electrical faults result in the formation of more high-molecular-weight by-products. Moreover, different fault intensities lead to the aggregation or fragmentation of degradation particles. Reference [24] further revealed that the type, duration, and frequency of electrical discharges are closely related to the nature and quantity of the aging products. Reference [25] performed quantitative analyses to monitor gas evolution under varying discharge intensities and types, showing that partial discharges mainly produce methane, while breakdowns and arc discharges predominantly generate acetylene. Among these, arc discharges—with their higher energy—produce significantly greater amounts of gas compared to other discharge types.

Reference [21] experimentally demonstrated that the synergistic effects of electrical and thermal stresses significantly accelerate the aging process of insulating oil. Specifically, thermal stress enhances oxidative chain reactions and reduces oil viscosity, which leads to an uneven electric field distribution and potentially triggers partial discharges. Meanwhile, electrical aging significantly reduces interfacial tension by promoting sludge formation. These combined effects result in a decrease in breakdown voltage exceeding 30%. Reference [26] designed and constructed an electrothermal stress testing apparatus, revealing that electrothermal stress further accelerates the aging of oil-paper insulation compared to single-factor stress. Reference [27] emphasizes that trace metal elements, such as copper and iron, catalyze oxidation and sulfidation reactions, thereby accelerating the degradation of insulating oil.

Given the synergistic effects of electrical and thermal stresses, the development of nano-modified insulating oil with enhanced dielectric and thermal properties—utilizing inert gas sealing and metal passivation techniques to inhibit catalytic degradation—has become a key strategy for mitigating insulation degradation and improving the operational reliability of power equipment.

III. Aging Forms and Mechanisms of Insulation Paper

Cellulose-based insulating paper serves as the primary insulation material in transformers and high-voltage bushings, predominantly composed of α-cellulose, hemicellulose, and trace amounts of lignin [28]. The aging mechanisms of insulation paper can be categorized into thermal degradation, hydrolysis, oxidative degradation, electrical aging, and mechanical stress-induced deterioration, with thermal aging identified as the predominant factor [29]. During extended transformer operation, the degradation of insulating oil and the aging of insulation paper demonstrate a synergistic interaction, as illustrated in Fig. 2.

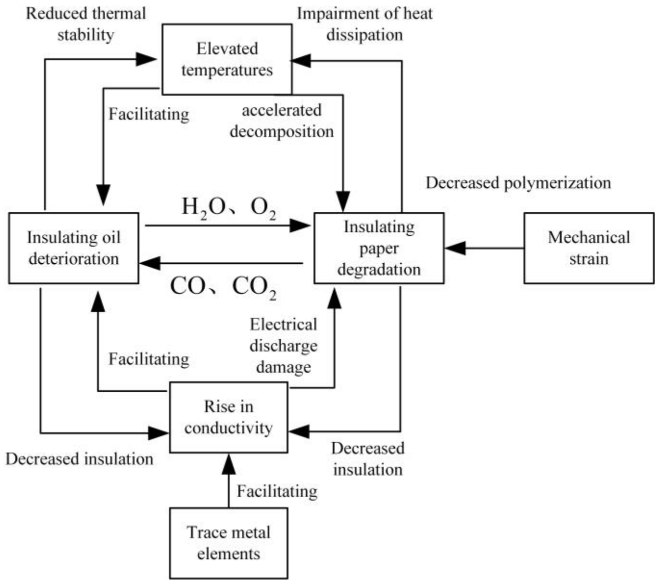

Fig. 2. Aging Mechanisms of the Oil-Paper Insulation Systems

A. *Thermal Aging of Cellulose Insulating Paper*

The heat generated during transformer operation induces both thermal degradation and oxidative reactions in the insulating paper, establishing temperature as a primary driver of cellulose aging. According to Arrhenius' law, the rate of chemical reactions increases exponentially with temperature. V. M. Montsinger was the first to propose the "10℃ rule" for insulation aging, which states that each 10 ℃ rise in temperature halves the service life of insulating materials[30].

However, the 10 ℃ rule is not universally applicable to all insulation systems due to variations in material composition, environmental conditions, engineering practices, and standardization criteria[31]. Accordingly, standards such as IEC 60076-7 and IEEE C57.91-2011 specify temperature-aging increments of 6 ℃ and 8 ℃, respectively[32][33].

Acid-Catalyzed Hydrolysis: $$(C_6H_{10}O_5)_n + nH_2O \xrightarrow{H^+} nC_6H_{12}O_6$$

Oxidative Degradation: $$(C_6H_{10}O_5)_n + O_2 \xrightarrow{\Delta} (C_6H_{10}O_5)_{n-k} + kCO + kCO_2 + H_2O$$

Metal - Catalyzed Degradation: $$(C_6H_{10}O_5)_n + Fe^{2+} / Cu^{+} \xrightarrow{H_2O} (C_6H_{10}O_5)_{n-m} + m(C_5H_4O_2) + H_2O$$

Thermal-Induced Cracking: $$(C_6H_{10}O_5)_n \xrightarrow{\Delta} (C_6H_{10}O_5)_{n-p} + pCO + pCO_2 + \text{Carbon residue}$$

Fig. 3. Reactions that occur when insulating paper is thermally aged

These variations can be quantitatively assessed using the Arrhenius equation, which effectively captures the differences in aging behavior across various materials and operating conditions.

$$\ln L = \ln A + B / T \quad (1)$$

In (1), A and B denote specific rate constants associated with distinct aging reactions. L represents the lifetime of the insulating material, while T indicates the absolute temperature measured in Kelvin.

When transformer operating temperatures consistently exceed 105 ℃ , the glycosidic bonds within cellulose molecular chains begin to break, leading to a progressive reduction in the Degree of Polymerization (DP). The aging state of cellulose insulation paper is commonly evaluated by measuring its DP; values above 2000 indicate excellent insulation integrity, whereas values below 200 suggest severe degradation[34].At elevated temperatures, the thermal also decomposition of cellulose produces furfural, a distinctive aging byproduct. Since furfural is non-volatile in oil and derives exclusively from cellulose degradation, its concentration in transformer oil serves as a key indicator of insulation aging. In practice, furfural content (threshold: 0.5 mg/L) and acid value (threshold: ≤ 0.1 mg KOH/g) are widely adopted as early warning indicators for oil-immersed transformer aging[35]. Thermal oxidation also generates quinone-based chromophores, gradually changing the color of the insulating paper from light yellow to dark brown[36]. Moisture plays a dual role in the aging process: it penetrates cellulose intermolecular spaces and, in the presence of H^+ ions, catalyzes the hydrolytic cleavage of β -1,4-glycosidic bonds while generating hydroxyl radicals, which accelerates the decline in DP. Concurrently, moisture reacts with acidic degradation products in the oil to form ionic conduction pathways, intensifying partial discharges and promoting further oxidation of furfural into organic acids. This initiates a cascading "hydrolysis – acidification – discharge" degradation cycle[37]. Moreover, under elevated temperatures and strong electric fields, oxygen oxidizes hydroxyl groups in cellulose into carbonyl and carboxyl groups, destabilizing the molecular structure. Metal ions such as copper and iron further catalyze these oxidation reactions, significantly accelerating the aging rate. The relevant chemical mechanisms are illustrated in Fig. 3.

B. Electrical Aging of Cellulose Insulating Paper

The electrical aging of cellulose insulating paper is a complex process influenced by the synergistic effects of electric field intensity, temperature, humidity, and dissolved gases in the insulating oil. Under strong electric fields, the presence of gas voids or impurities within the paper can initiate partial discharges. Although these discharges may not immediately lead to breakdown, they tend to develop progressively under sustained voltage stress, ultimately resulting in dielectric failure [38][39].

The mechanisms contributing to electrical aging of insulating paper can be summarized as follows:

1） Electron and ion bombardment: Gas ionization in the oil generates electrons and ions, which attack the cellulose molecular chains, cleaving glycosidic bonds and thereby reducing the DP.

2） Thermal effects: Localized heat generated by discharge raises the temperature within micro-defects, inducing thermal aging and potentially causing mechanical damage due to gas expansion.

3） Chemical degradation: Strongly oxidative and acidic gases produced during partial discharge corrode the polymer structure of the insulating paper.

4） Radiation effects: Intense ion recombination in the discharge zone emits high-energy radiation, leading to molecular decomposition and structural changes in the paper.

Reference [40] speculated that direct current (DC) stress can accelerate the oxidative degradation of insulating paperboard. Reference [37] analyzed the surface flashover voltage behavior of oil-paper insulation based on space charge theory, concluding that both alternating current (AC) and DC electric fields increase the likelihood of discharge and elevate the risk of insulation breakdown. Reference [41] examined the microscopic behavior of α-poly(vinylidene fluoride) (PVDF) under electric fields, revealing that prolonged surface polarization leads to gradual structural destabilization, which indirectly reflects the adverse effects of electric stress on insulation materials. Additionally, reference [42] investigated the long-term effects of electric field stress on the functional groups and frequency-domain dielectric response of resin-impregnated paper (RIP). The study revealed a decrease in ether bonds and an increase in hydroxyl groups, alongside a continuous rise in both the dielectric constant and dielectric loss, indicating progressive material degradation. Additionally, reference [43] conducted molecular dynamics simulations of cellulose insulating paper under various influencing factors. The results demonstrated that electric field stress alters the bond lengths of cellulose chemical structures, rendering the bonds more susceptible to breakage. This process accelerates the reduction in the degree of polymerization, ultimately leading to the deterioration of insulation performance.

Current studies on electrical stress-induced aging of cellulose insulation remain limited in both scope and depth. Existing models are inadequate in comprehensively explaining the aging process under complex electric stress conditions. Consequently, there is an urgent need to develop a cross-scale theoretical model that integrates space charge distribution, free radical reaction kinetics, and microstructural evolution. Such a model would facilitate a multidimensional understanding of the synergistic interactions between electrical and thermal aging, providing a robust theoretical foundation for designing effective insulation aging mitigation strategies.

C. Mechanical Aging of Cellulose Insulation Paper

During transformer operation, the insulation paper is subjected to mechanical stresses arising from temperature fluctuations, electromagnetic vibrations, and external mechanical shocks. Temperature variations lead to differential expansion coefficients between oil and paper, resulting in cyclic tensile-compressive deformation. Over time, the hydrogen bonds between cellulose chains weaken, causing fiber structure relaxation and the initiation of microcracks[44]. Additionally, load fluctuations and short-circuit impacts induce winding vibrations, subjecting the insulation paper to alternating shear stresses. These stresses are particularly concentrated at the winding ends and spacer contact regions, resulting in fiber slippage, pore expansion, and crack accumulation, ultimately reducing the elastic modulus and mechanical integrity of the insulation paper[45]. Research has shown that higher impact intensities and frequencies significantly increase the surface roughness and cracking of insulating paper, especially under thermally aged conditions, leading to a sharp decline in breakdown voltage[46]. Furthermore, studies indicate that mechanical stress has a more pronounced effect on insulating materials compared to thermal and electrical stresses[47]. Additionally, it has been found that mechanical stress significantly accelerates the transition of cellulose from crystalline to amorphous regions at the microscopic scale, thereby intensifying material degradation[48].

Research on nano-modified insulating paper has shown that incorporating nanofillers enhances the interfacial bonding between cellulose fibers, thereby improving both tensile strength and fatigue resistance. Reference [49] validated the superior performance of these materials under combined mechanical and thermal stresses. Moreover, Reference [50] emphasized the pivotal role of crystalline structure in determining microscale mechanical behavior, demonstrating that increased crystallinity contributes to higher rigidity and improved shear resistance.

Therefore, mechanical stress must be systematically addressed in both the design and maintenance of transformers. For aging transformers, mitigation measures such as the installation of shock absorbers, reinforcement of winding supports, and incorporation of flexible joints can effectively alleviate stress accumulation and transfer. In newly designed transformers, optimizing the core structure to minimize leakage-field-induced mechanical loads, along with prioritizing the use of nano-modified, high-crystallinity insulating paper, can significantly enhance the long-term mechanical stability and reliability of the insulation system.

IV. Aging Detection of Oil-immersed Transformer Insulation Systems

A. Non-Electrical Diagnostic Methods for Oil-Paper Insulation Systems

Non-electrical diagnostics function as the foundational approach for assessing the health of power equipment, encapsulated in the principles of 'look, listen, question, and feel.' This methodology emphasizes the identification of potential risks from a physicochemical perspective. The primary techniques employed include: DP analysis of insulating paper, Dissolved Gas Analysis (DGA) in oil, space charge measurement of insulating paper, moisture content evaluation of oil-paper insulation, and winding temperature assessment.

1) Degree of Polymerization Analysis of Cellulose Insulating Paper

The DP is widely recognized as the most direct and reliable indicator for characterizing the aging condition of oil-paper insulation. The average DP of cellulose chains is typically determined through chemical dissolution methods. In this process, cellulose insulation paper is completely dissolved in solvents such as cupriethylenediamine (CED) or N-methylmorpholine-N-oxide (NMMO), and the resulting solution is analyzed using either a Ubbelohde viscometer (UVM) or a rotational viscometer.

The DP is calculated using the Mark–Houwink equation.

$$\eta = K \cdot M^{a} \tag{2}$$

In (2), K and a are empirical constants that depend on the specific solvent–solute system, while M denotes the molecular weight of the polymer.

Multiple measurements are typically averaged to determine the molecular weight of cellulose, which is subsequently converted into the DP. However, this process relies on destructive sampling and viscosity-based methods, which are complex to implement and exhibit significant variability in results, thereby limiting their applicability in engineering practice. Similarly, offline assessment techniques based on tensile strength and scanning electron microscopy (SEM) morphological observation, while intuitive, are also constrained by the necessity of destructive sampling[51].

To address these limitations, Chongqing University proposed a novel diagnostic technique that integrates ultrasonic signal features with a neural network model. This method effectively captures alterations in sound velocity and frequency-domain attenuation characteristics induced by cellulose chain scission, facilitating non-invasive degradation prediction. The final validation demonstrated an accuracy exceeding 90%. However, its sensitivity to environmental factors continues to limit its field applications[52].

In recent years, numerous researchers have investigated the application of near-infrared (NIR) spectroscopy for measuring the DP of cellulose insulation paper. Although this method can correlate DP with characteristic peak shifts, it is significantly hindered by interference from aging byproducts present in the oil[53]. In contrast, terahertz (THz) absorption spectroscopy presents a promising alternative by detecting low-energy vibrational modes of cellulose molecules. This technique allows for non-destructive detection through the oil layer while effectively suppressing interference from impurities. Reference [54] indicates that the self-similarity index derived from THz spectral features demonstrates a strong linear correlation with DP values, with a correlation coefficient exceeding 0.9. Currently, terahertz technology has entered the engineering validation stage; however, it remains essential to establish a standard spectral library for various types of insulating paper and to quantify the impact of temperature gradients on characteristic parameters. This is crucial for addressing the challenges of adapting to complex field working conditions and facilitating the technological transition from 'destructive sampling and laboratory analysis' to 'in situ non-destructive and intelligent diagnosis'.

2) Dissolved Gas Analysis in Transformer Insulating Oil

DGA is a widely utilized diagnostic technique that assesses the aging condition and identifies fault types in transformer insulation systems by measuring the concentration and ratios of seven characteristic gases dissolved in the insulating oil[55][56].

As shown in TABLE I, hydrogen and ethyne are typically associated with partial discharges; methane, ethane, and ethylene primarily originate from oil cracking; while carbon monoxide and carbon dioxide are characteristic byproducts of cellulose insulation oxidation[57]. However, several studies suggest that CO and CO_2 may also originate from a combination of sources, including the degradation of insulating paper, oil decomposition, and even air ingress. Therefore, relying solely on the concentration of individual gases may lead to misdiagnosis. To enhance diagnostic accuracy, a comprehensive assessment that considers all seven key fault gases—along with diagnostic models such as the IEC three-ratio method and the Duval pentagon diagram—is essential for cross-verification. Despite their widespread application, traditional DGA methods generally exhibit limited diagnostic accuracy, often falling below 90%[58]. To address these limitations, recent studies have proposed integrating multi-parameter analysis with machine learning algorithms[59]. This approach facilitates the construction of probabilistic fault maps, which improve the differentiation of fault types such as thermal faults, electrical discharges, and other aging-related mechanisms. Consequently, DGA is evolving from conventional single-gas interpretation toward a more intelligent, multi-modal diagnostic framework.

TABLE I
ANALYSIS OF DISSOLVED GASES IN INSULATING OIL

Gas type	Common Types of Faults
hydrogen	transformer partial discharge and low-energy discharge
methane	oil overheating (low temperature <300 C°)
ethane	oil overheating (medium temperature < 500 C°)
ethylene	oil overheating (high temperatures >500 C°)
ethyne	high-energy discharge and short-circuit fault
Carbon monoxide、carbon dioxide	thermal aging of cellulose insulation paper

3) Space Charge Measurement in Oil-Paper Insulation

Space charge measurement techniques encompass the Pulsed Electro-Acoustic (PEA) method, thermal pulse method, pressure wave method, and numerical simulation approaches. Among these, the PEA technique is currently the most widely utilized and accurate method, particularly effective for characterizing charge behavior in insulating materials, especially in oil-paper insulation systems. The PEA method involves applying high-voltage pulses to the test sample, which induces internal space charge vibrations that generate minute acoustic signals. These signals are detected by piezoelectric sensors and converted into electrical signals, subsequently used to reconstruct the space charge distribution profile with a spatial resolution of up to 0.1 mm. This method facilitates the quantitative analysis of critical parameters such as charge dissipation rate, carrier mobility, and the thickness of anisotropic charge layers. The PEA technique has demonstrated effectiveness in identifying abnormal charge trapping behavior associated with cellulose chain scission and the introduction of polar functional groups[60][61]. Other techniques, such as the thermal pulse method, depend on temperature gradients to drive charge migration and are more suited for thin polymer film systems. The pressure wave method employs transient mechanical excitation but is limited by its sensitivity. Numerical simulations primarily serve theoretical modeling and aging prediction, with accuracy significantly reliant on precise material parameters. In comparison, the PEA method provides superior measurement precision and spatial resolution, establishing it as the most reliable experimental approach for investigating space charge effects[62][63].

However, the application of PEA in engineering practice remains limited due to its requirement for destructive sampling, incompatibility with complex transformer geometries, and susceptibility to electromagnetic interference. To address these challenges, North China Electric Power University (NCEPU) has developed a fiber-coupled, non-contact optoelectronic technology that enhances immunity to electromagnetic interference, thereby paving the way for future online monitoring of space charge distribution[64]. Additionally, reference [65] introduced a PEA-based system for polyethylene cable insulation, which successfully achieved high-resolution charge profiling; however, no implementation has yet been developed for cellulose insulation paper under in-service transformer conditions.

Future research on space charge should focus on the following aspects:

1） Reducing acoustic noise generated by microbubbles and solid impurities in oil to improve the signal-to-noise ratio;
2） Establishing reliable mapping models between space charge characteristics and insulation aging states for quantitative evaluation;
3） Developing edge-intelligent diagnostic systems integrated with data-driven analysis to enable online monitoring, achieving real-time aging assessment and lifetime prediction of oil-paper insulation systems.

4) Other Diagnostic and Detection Methods

The moisture content, furfural concentration, and oil temperature in transformer insulating oil are critical indicators for assessing the health of insulation systems. The thermal stability of these systems is typically evaluated through long-term monitoring of transformer oil temperature, in conjunction with load conditions and ambient temperature variations[66]. However, due to the influence of seasonal and environmental factors, assessing oil temperature alone tends to be complex and delayed, thereby necessitating a multi-parameter analysis for accurate diagnosis.

Moisture content in insulating oil is typically measured using Karl Fischer titration or infrared spectroscopy. In contrast, the direct measurement of moisture in insulation paper presents significant challenges. To estimate the moisture content in the paper, researchers have proposed an indirect estimation method that utilizes oil moisture content and temperature data in conjunction with a water balance model, such as the Oommen and Norris curves. These approaches have undergone preliminary validation in engineering applications, demonstrating considerable practicality. Monitoring moisture content not only aids in identifying potential fault risks but also contributes to the prevention of insulation deterioration[67].

Furfural, a specific marker for the aging of insulating paper, serves as a critical warning indicator when its concentration exceeds 0.5 mg/L, indicative of mid-stage aging, or 4 mg/L, which signifies the end-of-life condition, as specified in the DL/T 596-1996 standard[68]. Among the existing detection technologies, high-performance liquid chromatography (HPLC) is noted for its high accuracy [69][70]. However, it is limited by its applicability in field settings and its complex operational requirements. To enhance detection efficiency, infrared spectroscopy has been utilized, capitalizing on the characteristic carbonyl absorption peak at 1677 cm^{-1} for quantitative analysis, achieving a detection limit as low as 0.1 mg/L with commendable repeatability and practicality[71]. Furthermore, reference [72] has proposed a surface-enhanced Raman scattering (SERS) substrate based on Cu–graphene (porous)–AgNPs, which enables the simultaneous and sensitive quantification of furfural, acetone, and formaldehyde.

Recent studies indicate that future diagnostic techniques for transformer insulation aging will evolve toward integrated solutions that feature online monitoring, real-time responsiveness, high accuracy, and intelligent analytics. These advancements aim to meet the practical demands of assessing the health condition of oil-paper insulation systems in complex operational environments.

B. Electrical Diagnostic Techniques for Oil-Paper Insulation Systems

Electrical diagnostic techniques serve as "precision instruments" for assessing the electrical performance of transformers, providing real-time and rapid insights into their operational status. By continuously monitoring key electrical parameters—such as the dielectric loss factor (tan δ), insulation resistance, Polarization Index (PI), and dielectric constant—these methods facilitate non-invasive evaluation and protection of the oil-paper insulation systems[73]. The tan δ value significantly increases with a decrease in the DP of cellulose in insulating paper, an increase in oil impurities, or elevated moisture content. Insulation resistance and the polarization index are also effective indicators of the insulation system's condition. When the system is exposed to moisture or conductive aging by-products, insulation resistance decreases, and the PI deviates from normal values. A PI value lower than 2.0 typically signifies serious moisture ingress or insulation aging.

Dielectric response techniques enhance diagnostic accuracy by analyzing polarization and relaxation behaviors. These techniques encompass time-domain methods, such as the Return Voltage Method (RVM) and Polarization and Depolarization Current (PDC), as well as frequency-domain analysis through Frequency Domain Spectroscopy (FDS).

1) Time-Domain Dielectric Response Techniques

RVM evaluates the condition of insulation by measuring both the peak recovery voltage and the initial slope during the depolarization phase, both of which tend to increase with insulation aging. Studies have demonstrated that the semi-peak stabilization time also extends as oil-paper insulation degrades, making it a useful parameter for distinguishing between different aging states[74][75]. However, in practical engineering applications, RVM is susceptible to residual charge interference, which limits the diagnostic information it can provide. Consequently, it is generally regarded as less competitive compared to the PDC method and FDS.

The PDC technique analyzes polarization and depolarization currents to quantify both oil conductivity and moisture content in insulation paper. The initial segment of the polarization current curve reflects the concentration of colloidal particles in the oil, while the tail end is correlated with the DP of cellulose and the moisture content[79]-[78].

Future research should focus on enhancing the accuracy and generalizability of the assessment mechanisms for aging and moisture degradation.

2) Frequency-Domain Dielectric Response Techniques

FDS is currently one of the most widely adopted techniques for diagnosing dielectric response. It evaluates the condition of oil-paper insulation by measuring the complex capacitance and dielectric loss spectra over a broad frequency range of 0.1 mHz to 1 kHz, thereby providing multidimensional insights into the material's microscopic polarization mechanisms.

This technique, which examines the microscopic polarization mechanism, is similar to PDC in that the characteristics of its curves are influenced by the carrier polarization rate[79]. Specifically, the low-frequency range is highly sensitive to the moisture content in the paper, the mid-frequency range reflects the conductivity of the oil and structural changes in the paper, while the high-frequency range primarily indicates the aging degree of cellulose materials[80][81].Reference [82] demonstrates that temperature significantly impacts FDS measurements. As temperature increases, both the real and imaginary components of the complex capacitance rise, causing their intersection to shift toward higher frequencies. Consequently, effective temperature correction is essential for accurate and comparable aging assessments of oil-paper insulation. Reference [83] proposes a dual frequency–temperature shift method, introducing correction coefficients to characterize the distribution of multiple relaxation times. Following correction, the low-frequency curve becomes smoother, and the deviation from measured DC conductivity decreases from over 70% (in traditional models) to less than 15%.

In addition, adopting an AC conductivity model that incorporates multiple relaxation polarizations can effectively address the traditional underestimation of low-frequency conductivity.

3) Partial Discharge Detection Techniques

Partial Discharge (PD) measurement is a fundamental diagnostic technique employed to identify insulation aging and potential faults in transformers. This technique is often associated with phenomena such as electromagnetic pulses, ultrasonic waves, light radiation, and gas release[84].

PD detection technology is primarily categorized into electrical signal detection and acoustic signal detection. Electrical signal detection encompasses methods such as pulse current and Ultra-High Frequency (UHF) detection, while acoustic signal detection employs piezoelectric or fiber optic ultrasonic sensors to capture the acoustic signals generated by partial discharge[85]. The pulse current method demonstrates high accuracy in laboratory environments; however, its application in field settings is frequently hindered by electromagnetic interference. UHF detection enhances interference resistance by identifying electromagnetic radiation above 300 MHz, yet it encounters challenges in quantifying discharge levels and is relatively expensive. Conversely, acoustic signal methods present advantages such as non-invasiveness and cost-effectiveness; however, they are vulnerable to mechanical noise interference and exhibit limited detection capabilities for low-energy discharges or deep-seated locations. Reference [86] indicates that neural networks can optimize the measurement data of partial discharge signals, thereby enhancing measurement accuracy. Additionally, studies suggest the use of multiple sensors to form an array of electrical, acoustic, and optical sensors for precise localization and measurement of PD[87][88].

In the future, PD detection is expected to advance towards high-precision positioning, multi-modal information fusion, and intelligent decision-making. By integrating various types of sensors, including ultra-high frequency, electroacoustic, and fiber optic sensors, complementary verification of signals and spatial collaborative sensing can be achieved. Moreover, combining deep learning algorithms to model and analyze discharge patterns and evolution trends enables early identification and accurate assessment of the degradation process of paper insulation materials under complex operating conditions. This approach provides data-driven technical support for condition monitoring and fault prevention in critical power equipment.

TABLE II
INSULATION AGING DETECTION IN OIL-IMMERSED TRANSFORMERS

Methods	Advantages	Limitations
	Non-electricity	
DP	Direct and accurate aging indicator	Destructive sampling; requires shutdown
Tensile Strength	Strongly correlated with insulation degradation	Destructive and operationally complex
DGA	Sensitive to fault gases	Limited accuracy
Moisture (Oil/Paper)	Accurately reflects insulation moisture	Uneven water distribution
Oil Temperature Measurement	Simple and cost-effective	Unreliable under fluctuating load
PEA	High-resolution space charge profiling	Time-consuming and destructive sampling
	Electricity	
FDS	Non-destructive; provides rich diagnostic data	High equipment cost; complex interpretation
RVM	Rapid initial screening	Susceptible to residual charge interference
PDC	Compact and easy to operate	Sensitive to temperature variations
PD	Online real-time monitoring	Susceptible to environmental disturbance

As shown in TABLE III, non-electrical diagnostics can accurately quantify the degree of aging in oil-paper insulation; however, these methods are often time-consuming and require substantial human and material resources. Furthermore, measuring key parameters such as polymerization degree and tensile strength typically involves destructive sampling, which can disrupt the continuous operation of transformers. In contrast, electrical diagnostics primarily depend on electrical characteristic parameters to provide real-time monitoring and early warning for power systems; however, they are prone to interference and may not accurately reflect the actual aging condition of insulation materials. With the ongoing advancement of smart sensing and data analysis technologies, future insulation diagnostics are anticipated to integrate both electrical and non-electrical methods, thus achieving a more comprehensive, accurate, rapid, and intelligent assessment of transformer insulation health.

V. CONCLUSION

The aging of oil-immersed transformer insulation is a critical issue that impacts the safe operation of power systems. Investigating the mechanisms of multi-physical field coupling aging and developing accurate life assessment techniques possess both theoretical significance and practical engineering value.

From the perspective of synergistic aging in oil–paper insulation systems, active substances generated by the thermal-oxidative degradation of insulating oil can induce cellulose chain scission in the paper. Subsequently, degradation products from the insulating paper further catalyze oil oxidation, creating a chain reaction characterized by "oil deterioration – paper degradation." This multifaceted interaction, which includes electrical, thermal, chemical, and mechanical stresses, serves as the fundamental driving force behind the accelerated deterioration of oil-paper insulation systems. However, current research on anti-aging strategies and life prediction for insulation systems remains insufficient and requires further investigation.

1) Currently, both mineral-based and plant-based insulating oils possess distinct advantages and disadvantages. Consequently, future research should prioritize the development of high-stability synthetic ester insulating oils or modified plant oils. For instance, molecular structure design, informed by quantum chemical calculations, can establish a structure-property relationship that connects macroscopic performance with microscopic molecular parameters. The incorporation of functionalized nanoparticles, such as hydroxylated graphene, can significantly enhance the performance of insulating oils. Furthermore, investigating cellulose-based composite materials, including aramid paper and high-temperature-resistant polymers such as polycarbonate, is essential for improving the thermal stability and mechanical strength of insulating paper. Concurrently, systematic research on the synergistic mechanisms between antioxidants and metal passivators is necessary to inhibit metal ion-catalyzed degradation reactions, thereby enhancing the long-term stability of insulating materials.

2)Traditional diagnostic methods are often hindered by response delays and a limited capacity to assess insulation aging. Although non-electrical diagnostic techniques can yield relatively accurate estimates of the lifespan of insulation systems, they typically necessitate destructive sampling and lack real-time monitoring capabilities. Conversely, electrical diagnostics can be monitored online in real time; however, they face challenges in effectively capturing the coupled aging behavior of insulating oil and insulating paper. Future research should prioritize the development of online sensors that target key physical-chemical indicators, integrating them with electrical diagnostic techniques such as partial discharge (PD) and frequency domain spectrum (FDS) to facilitate real-time, comprehensive detection that encompasses both electrical and physical-chemical characteristics. By amalgamating feature data from multiple physical domains, the influence of single-variable anomalies can be mitigated, thereby enhancing diagnostic accuracy and robustness. This methodology is particularly well-suited for the harsh environments within transformers and aids in the establishment of intelligent online monitoring networks based on multi-parameter integration.

3) Most existing life prediction models inadequately account for the coupled effects of multiple stress factors, including thermal, electrical, and mechanical stresses. Future research should focus on integrating operational, diagnostic, and environmental data to establish a comprehensive multi-source database. Advanced deep learning models, such as Long Short-Term Memory (LSTM) networks and Convolutional Neural Networks (CNNs), should be employed to analyze and iteratively update transformer status data, thereby enhancing the accuracy of service life predictions for insulation systems. By incorporating these models into a digital twin framework, the aging behavior under various operating conditions can be simulated, facilitating early warnings regarding insulation conditions. Furthermore, it is essential to develop edge computing frameworks to embed predictive models within field devices, thereby improving real-time decision-making and intelligent maintenance scheduling—critical components for advancing smart grid systems.

4) Current research lacks a comprehensive analysis of the molecular mechanisms underlying cellulose chain breakage, space charge accumulation, and interfacial effects. To address this gap, molecular dynamics simulations can be employed to elucidate the molecular breakage pathways of cellulose under the coupled effects of thermal, electrical, and mechanical stresses. Furthermore, it is essential to investigate aging mechanisms under multi-physics coupling conditions, including alternating and direct current harmonic electric fields, thermal gradients, and mechanical vibrations, as well as to elucidate the effects of nanomaterial modifications on carrier trap distribution and density. Advancing our understanding of these microscopic-scale mechanisms will provide a theoretical foundation for developing new diagnostic technologies, thereby facilitating the transition of transformer insulation diagnosis from empirical methods to mechanism-based approaches.

5) Current standards, such as IEC 60599, exhibit notable limitations in accommodating dielectric response testing and space charge measurement under varying temperature conditions. Consequently, these standards are insufficient for accurate insulation aging assessments in complex operational environments. There is an urgent need to develop more standardized calibration protocols for temperature and humidity, along with clearly defined temperature compensation parameters, to enhance the reliability of diagnostic techniques such as Frequency Domain Spectroscopy (FDS) and Polarization and Depolarization Current (PDC) analysis. Furthermore, the establishment of a global insulation aging database is worth considering, as it would support the revision and extension of existing ISO/IEC standards to encompass emerging materials such as synthetic esters and nano-modified insulating oil. The development of certified reference materials (e.g., insulation paper with specific degrees of polymerization) and standardized testing methodologies would further improve the consistency and generalizability of diagnostic results, thereby providing a robust foundation for the full life-cycle management of power equipment.

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