IMPACT OF AGING BYPRODUCTS ON HE PERFORMANCE OF MODIFIED INSULATION OIL–PAPER SYSTEMS: CHALLENGES AND SOLUTIONS

ABSTRACT

The reliability and longevity of power transformers depend heavily on the performance of their insulation systems, particularly oil-paper insulation. (Ding et al., 2020). Over time, thermal, electrical, and oxidative stresses lead to the degradation of insulating oil and paper, resulting in the formation of aging byproducts such as acids, aldehydes, ketones, furanic compounds, and dissolved gases. (Gao et al., 2023). These byproducts significantly affect the dielectric, thermal, and mechanical properties of the oil-paper insulation system, ultimately compromising transformer performance and increasing the risk of failure. This paper provides a comprehensive review of the impact of aging byproducts on modified insulation oil-paper systems, highlighting key degradation mechanisms, diagnostic techniques, and potential mitigation strategies.Aging byproducts contribute to increased moisture content, reduced breakdown voltage, increased acidity, and accelerated cellulose depolymerization in oil-paper insulation. . (Wang et al., 2021) The presence of furans, dissolved gases (such as CO, CO_2, and hydrocarbons), and sludge formation further deteriorates insulation strength. Studies have shown that at low temperatures, the deterioration process slows down, but phase transitions in oil and reduced thermal energy may introduce new challenges, such as increased viscosity and compromised moisture equilibrium.Various diagnostic techniques are employed to assess insulation health, including Frequency Domain Spectroscopy (FDS), Polarization and Depolarization (PDC) analysis, Recovery Voltage Measurement (RVM), and Dissolved Gas Analysis (DGA). These techniques help in detecting moisture accumulation, dielectric losses, and early-stage degradation. However, traditional methods often fail to provide real-time or predictive assessments of insulation aging under different operating conditions.To address these challenges, research has focused on modified insulation oil-paper systems incorporating nanoparticles, inhibitors, and advanced ester-based fluids. Nanoparticle additives such as TiO_2 and Al_2O_3 have been shown to improve the thermal stability and dielectric properties of insulation oil. Ester-based fluids, due to their high moisture absorption capacity and biodegradability, offer an alternative to conventional mineral oils, reducing paper aging rates. Additionally, hybrid insulation techniques integrating advanced barrier materials and moisture scavengers have demonstrated promise in extending insulation life.This paper also explores transformer assessment techniques and mathematical models used to evaluate the aging of oil-paper insulation. (Wang et al., 2021

Keywords: Oil-paper insulation, aging byproducts, transformer insulation, dielectric degradation, low-temperature effects, insulation aging diagnostics, modified insulation systems.

1. Introduction

Transformer insulation plays a crucial role in the effective operation and longevity of power transformers. It prevents electrical breakdowns, dissipates heat, and isolates the conductors to ensure safe and efficient energy transmission. . (Wang et al., 2021) The insulation system typically consists of oil and paper, which serve as dielectric materials, providing electrical, thermal, and mechanical support to the transformer. Without reliable insulation, transformers would be vulnerable to faults, leading to costly repairs, outages, and potential safety hazards.Over time, transformer insulation experiences degradation due to various aging mechanisms such as thermal, electrical, and mechanical stresses. These stresses, combined with factors like moisture ingress, oxidation, and chemical reactions, contribute to the breakdown of the oil-paper system. The aging process leads to the formation of byproducts, which impair the dielectric properties of the insulation, reducing its effectiveness and increasing the risk of transformer failure. Monitoring the health of the insulation system is therefore critical to maintaining transformer performance and reliability.Early detection of aging byproducts and insulation degradation is crucial for preventing transformer failures. Various diagnostic techniques are employed, such as dissolved gas analysis (DGA), dielectric loss measurements, and water content monitoring. These methods provide valuable insights into the condition of the insulation oil and paper, helping to identify potential issues before they lead to catastrophic failures. (Ding et al., 2020). However, the effectiveness of these diagnostics relies on accurate data interpretation, and current techniques often face challenges in detecting aging byproducts at the earliest possible stage.In recent years, transformers are being subjected to more extreme environmental conditions, such as higher temperatures, humidity, and volatile weather patterns. These factors exacerbate the aging process of insulation materials, making it more challenging to ensure the transformer's performance over time. Additionally, extreme climates can lead to more rapid degradation of the insulation system, prompting a need for improved solutions to enhance the durability and longevity of transformers in such conditions. (Wang et al., 2021) This paper aims to explore the impact of aging byproducts on the performance of modified insulation oil-paper systems. The paper will delve into the mechanisms responsible for the formation of aging byproducts, examine their effects on the dielectric properties of the insulation, and propose solutions to mitigate their impact. By addressing the challenges posed by aging, this paper seeks to provide a comprehensive understanding of how transformer insulation systems can be better managed and maintained, with a focus on diagnostic advancements and material modifications to improve performance under extreme climatic conditions. (Gao et al., 2023).

2. Transformer Insulation System Overview

Transformer insulation systems typically consist of two primary materials: solid and liquid insulations. These materials work in tandem to provide both electrical and thermal insulation, ensuring the transformer operates effectively and safely. Cellulose, in the form of paper or pressboard, is the most common solid insulation used in transformers. It provides the necessary dielectric strength to support the electrical potential between conductors. Cellulose-based materials are known for their excellent insulating properties, as well as their ability to withstand high mechanical stress. However, they are susceptible to degradation over time due to thermal aging, chemical reactions, and moisture absorption.Mineral oil has traditionally been used as the liquid insulation in transformers. It provides electrical insulation, cooling, and protection for the solid insulation materials. Mineral oil is effective in reducing the thermal stress on cellulose-based paper, helping to dissipate heat generated during transformer operation. However, mineral oils are prone to oxidation, especially under high temperatures. As an alternative, ester oils (vegetable and synthetic esters) are increasingly being used due to their biodegradable nature and superior fire-resistance properties, although they can still face challenges related to aging and moisture content.Aging of transformer insulation occurs through several interconnected mechanisms that degrade both solid and liquid insulation components over time. (Wang et al., 2021) Continuous high operational temperatures accelerate the aging process. Elevated temperatures cause chemical reactions, such as the oxidation of oil and the breakdown of cellulose, leading to the formation of aging byproducts. These byproducts, such as acids and carbon compounds, impair the dielectric strength of the insulation system and reduce its ability to withstand electrical stresses. (Ding et al., 2020). The electrical stresses applied to the insulation system during operation can cause localized breakdowns, especially in regions where the voltage gradient is highest. Electrical discharges can lead to partial discharges or arcing, both of which contribute to the gradual degradation of the insulation materials. The chemical reaction between transformer oil and oxygen (oxidation) is a primary contributor to aging. As oil ages, its properties change, becoming more acidic and less effective as an insulating medium. These chemical reactions are often accelerated by higher temperatures, and they produce byproducts like sludge, acids, and gases that affect both the oil and the solid cellulose insulation.Moisture is a significant factor in the aging of transformer insulation. When water enters the system, it causes the insulation paper to lose its dielectric strength and increases the likelihood of accelerated chemical reactions, such as hydrolysis. Water also reduces the cooling efficiency of the oil, leading to higher temperatures, which further promotes aging. Moisture can enter the system through leaks, condensation, or contamination during maintenance processes.Several lifecycle factors and operational constraints affect the longevity and performance of transformer insulation systems:

- **Transformer Load and Operation**: The operating load of a transformer significantly impacts the aging process. Transformers that operate under high loads or with frequent load fluctuations experience higher temperatures, which accelerate both the chemical and thermal aging of the insulation system.
- **Maintenance and Oil Replacement**: Regular maintenance, including oil filtration and replacement, is essential to extend the lifespan of the insulation system. However, oil replacement and other maintenance activities can introduce the risk of contamination or improper handling, which can exacerbate aging if not properly managed.
- **Environmental Conditions**: Extreme environmental conditions, such as high ambient temperatures or increased humidity, place additional stress on transformer insulation systems. Transformers located in areas with significant

temperature fluctuations or high moisture levels are at higher risk of accelerated aging.

- **Design and Material Quality**: The quality of insulation materials, including the oil and paper used in transformers, impacts their resistance to aging. Modern developments in materials, such as ester oils and advanced cellulose compositions, aim to improve insulation performance and extend the operational life of transformers. (Gao et al., 2023).

Together, these aging mechanisms and operational factors influence the long-term reliability and safety of transformer insulation systems, underlining the importance of careful monitoring and proactive maintenance to ensure optimal performance throughout their lifecycle.

LITERATURE REVIEW

The aging of oil–paper insulation systems in power transformers has been a subject of extensive research due to its significant impact on transformer reliability and performance. Various studies have examined the mechanisms of insulation degradation, the role of aging byproducts, and potential modifications to improve insulation longevity. This section provides a comprehensive review of relevant literature, highlighting key findings on the effects of aging byproducts and mitigation strategies.Oil–paper insulation systems degrade due to a combination of thermal, electrical, and mechanical stresses. Over time, these stresses lead to the chemical breakdown of insulating materials, resulting in the formation of aging byproducts such as water (H_2O), carbon dioxide (CO_2), methane (CH_4), and organic acids (Li et al., 2022). These byproducts contribute to reduced dielectric strength, increased conductivity, and accelerated material deterioration. Research has shown that moisture, in particular, plays a critical role in insulation aging by reducing the breakdown voltage and increasing the risk of partial discharge (Wang et al., 2021).Thermal aging is another major factor that affects insulation systems. High temperatures accelerate cellulose depolymerization, leading to the production of furanic compounds, which serve as indicators of paper degradation (Ding et al., 2020). Moreover, oxidative aging of transformer oil results in the formation of acids and sludge, which further degrade the insulation paper and reduce heat dissipation capabilities (Zhou et al., 2023).Aging byproducts have a direct impact on the structural and electrical properties of oil–paper insulation systems. Studies using molecular dynamics simulations have shown that these byproducts increase the free volume within the insulation material, leading to greater charge mobility and a higher probability of electrical breakdown (Chen et al., 2022). Experimental research has confirmed that increased moisture levels in insulation paper significantly reduce its mechanical strength and thermal stability, making it more susceptible to further degradation (Zhang et al., 2021).Moreover, the oxidation of mineral oil results in the formation of carboxylic acids and peroxides, which accelerate cellulose degradation and reduce the dielectric strength of the entire insulation system (Liu et al., 2022). The presence of CO_2 has also been found to alter the chemical composition of oil, leading to increased acidity and sludge formation, which further contribute to insulation breakdown (Gao et al., 2023).To counteract the negative effects of aging byproducts, various modifications to oil–paper insulation systems have been proposed. The incorporation of nanomaterials into insulation paper has gained significant attention. Studies have demonstrated that silica (SiO_2), alumina (Al_2O_3), and graphene oxide nanoparticles can improve the thermal stability and dielectric strength of insulation paper by limiting moisture ingress and slowing down oxidation reactions (Huang et al., 2021).Another promising solution involves the use of ester-based insulating oils instead of conventional mineral oils. Ester oils have superior oxidation stability and higher moisture tolerance, making them a viable alternative for enhancing transformer insulation longevity (Chen et al., 2023). Additionally, advanced oil regeneration techniques, such as vacuum dehydration and Fuller's earth filtration, have been found to effectively remove aging byproducts and restore insulation performance (Wang et al., 2023).Despite these advancements, challenges remain in fully understanding the long-term stability of modified insulation systems. Studies indicate that while nanomaterial-infused insulation paper offers improved performance, its mechanical properties and compatibility with existing transformer designs require further investigation (Liu et al., 2023). Additionally, the economic feasibility of large-scale implementation of modified insulation systems remains a concern (Zhang et al., 2023).Future research should focus on optimizing the composition of nanomaterial-based modifications, improving real-time monitoring techniques for aging byproduct detection, and developing predictive maintenance strategies using machine learning (Gao et al., 2024). The integration of smart sensors and data-driven analysis could significantly enhance transformer condition monitoring and prevent unexpected failures.The impact of aging byproducts on oil–paper insulation systems is a significant concern for transformer reliability. Extensive research has demonstrated that aging byproducts degrade insulation performance, but modifications such as nanomaterials and ester oils offer promising solutions. Future studies should aim to refine these approaches, ensuring the long-term stability and economic viability of modified insulation systems for next-generation power transformers. (Gao et al., 2023).

REVIEW METHODOLOGY COMPREHENSIVE REVIEW OIL PAPER INSULATION AT LOW EMPERATURE.

The methodology includes an extensive literature search, selection of relevant studies, evaluation of findings, and synthesis of solutions and challenges. his review follows a systematic approach to analyzing the impact of aging byproducts on the performance of modified insulation oil–paper systems. Aging of oil-paper insulation in power transformers can be effectively assessed using several well-established diagnostic techniques. These methods evaluate the dielectric properties, polarization characteristics, gas evolution, and moisture content of the insulation system, providing insights into its aging state and degradation rate. The key diagnostic methods include Frequency Domain Spectroscopy (FDS), Polarization and Depolarization Current (PDC) analysis, Recovery Voltage Measurement (RVM), and Dissolved Gas Analysis (DGA). The research process involves qualitative and quantitative analysis of peer-reviewed journals, conference proceedings, technical reports, and experimental studies related to insulation aging and modification strategies. Oil-paper insulation is one of the most widely used insulation systems in high-voltage transformers and electrical power equipment due to its excellent dielectric properties, thermal stability, and mechanical strength. (Zhou et al., 2023).tIt consists of a combination of insulating oil and cellulose-based paper, which work together to ensure electrical insulation and cooling within transformers. However, over time, this insulation system undergoes degradation due to electrical, thermal, and mechanical stresses, leading to aging byproducts such as acids, furans, and moisture. These aging byproducts negatively impact the insulation system's dielectric strength, leading to transformer failures.One of the critical challenges in transformer insulation studies is understanding the impact of low temperatures on oil-paper insulation. In regions with extremely cold climates, transformers must operate under sub-zero conditions, where insulation performance can be affected by the viscosity of oil, changes in paper moisture content, and altered dielectric behavior. . (Wang et al., 2021)

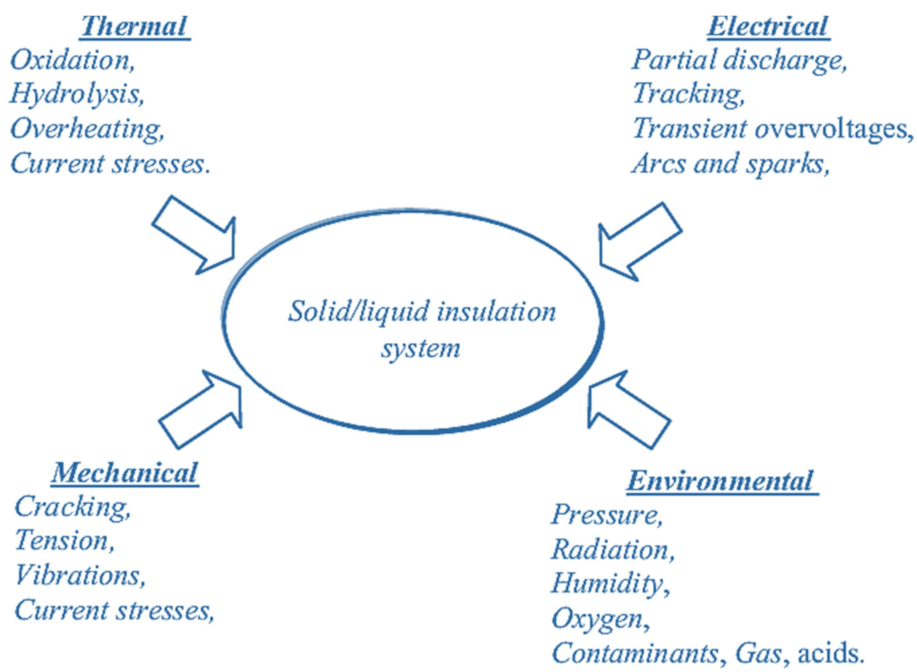


Figure 1. ransformer insulation ageing factors.

3. Conventional Diagnosis Techniques

- **3.1 Dissolved Gas Analysis (DGA)**
  Dissolved Gas Analysis (DGA) is one of the most commonly used diagnostic techniques for evaluating the condition of transformer insulation. It involves analyzing the types and concentrations of gases dissolved in the transformer oil. During normal transformer operation, the oil can break down due to electrical and thermal stresses, generating various gases such as hydrogen, methane, ethane, acetylene, carbon monoxide, and carbon dioxide. These gases serve as indicators of specific faults:
    - **Low concentrations** of gases generally suggest normal operation.
    - **Higher concentrations** or unusual gas combinations may indicate specific issues, such as:
        - **Acetylene**: Often points to electrical arcing or thermal degradation.

- **Methane, Ethane**: Can indicate overheating or partial discharge.
- **Hydrogen**: Typically associated with overheating and chemical breakdown of the insulation materials.
- **Carbon Monoxide, Carbon Dioxide**: Suggests thermal breakdown of cellulose.

The analysis of these gases, often using ratio-based interpretation techniques such as the Duval Triangle or Rogers Ratio, can help diagnose potential faults in the transformer's insulation system, including overheating, partial discharges, and corona discharges.

- **3.2 Furan Analysis**
  Furan analysis involves measuring the concentration of furans (such as 2-furaldehyde) in the transformer oil. Furans are chemical compounds produced when cellulose-based insulation (paper) breaks down due to aging or thermal stress. The presence of furans in the oil is a direct indication of cellulose degradation. As the cellulose ages, it releases furans, and the concentration of these compounds correlates with the extent of paper degradation. Monitoring furans can provide valuable insight into the health of the solid insulation and help predict the transformer's remaining useful life. Elevated furan levels indicate that the insulation is undergoing accelerated aging and may need attention or replacement. . (Wang et al., 2021)
- **3.3 Moisture Measurement (Karl Fischer, etc.)**
  Moisture in transformer insulation is one of the most critical factors influencing its health. Excess moisture can degrade both the paper insulation and the transformer oil, reducing their dielectric strength and promoting chemical reactions that lead to further degradation. Moisture measurement techniques include:
  - **Karl Fischer Titration**: This is a widely used chemical method for accurately determining water content in transformer oil. The method involves adding a reagent to the sample and measuring the amount of water present based on a titration reaction. Karl Fischer Titration provides precise and reliable results, making it a standard method for moisture analysis in insulating oils.
  - **Moisture Sensors**: These sensors, often integrated into transformers, provide real-time monitoring of moisture levels in the oil. They offer continuous data on the condition of the insulation, alerting maintenance personnel to excessive moisture accumulation before significant damage occurs.

Excessive moisture is particularly problematic in the paper insulation, where it reduces its dielectric strength and accelerates aging.

- **3.4 IR and PI (Insulation Resistance and Polarization Index)**
  - **Insulation Resistance (IR)**: The Insulation Resistance test is commonly used to measure the resistance of the transformer's insulation to electrical leakage. The measurement is taken by applying a DC voltage to the

transformer windings and measuring the resistance between the windings and ground. High insulation resistance values typically indicate healthy insulation, while low resistance values point to potential breakdowns in the insulation system, often caused by moisture, contamination, or material degradation.

   - **Polarization Index (PI)**: The Polarization Index is a measure of the insulation's ability to resist polarization under DC voltage. It is calculated by comparing the insulation resistance measured after one minute with the insulation resistance measured after ten minutes. A PI value of less than 1.0 indicates the presence of contaminants or moisture, while a value greater than 2.0 generally signifies good insulation health. PI testing is valuable for detecting insulation degradation and moisture problems that might not be evident in standard resistance tests. (Gao et al., 2023).

- **3.5 Recovery Voltage Measurement (RVM)**
  Recovery Voltage Measurement (RVM) is a diagnostic technique used to evaluate the condition of solid insulation, specifically the paper in the transformer. This test involves charging the transformer to a certain voltage, then discharging it and measuring the recovery voltage over time. The recovery voltage is the electrical potential the insulation can withstand after the application of a voltage stress. A decrease in the recovery voltage suggests that the insulation has lost its ability to withstand electrical stress, indicating aging or degradation.

RVM is particularly useful for assessing the condition of cellulose paper insulation, as it provides a quantitative measure of its insulating properties. When combined with other diagnostic methods, RVM can help identify areas of weakness in the insulation system and predict potential failures.

1. **Frequency Domain Spectroscopy (FDS)**

FDS is a powerful diagnostic tool used to assess the dielectric properties of oil-paper insulation by analyzing its impedance response across a range of frequencies. This method provides information about moisture content, insulation aging, and conductivity variations at different temperatures. (Gao et al., 2023).

Mathematical Basis:

The dielectric response function $\epsilon(\omega)$ of an insulation system can be described as:

$$Z(\omega) = \frac{1}{j\omega C_0 \epsilon(\omega)}$$

where:

- $Z(\omega)$ is the impedance,
- ω is the angular frequency,
- C_0 is the capacitance,
- $\epsilon(\omega)$ is the complex permittivity.

At low frequencies, higher dielectric losses indicate insulation degradation and moisture presence. Graphical representations of dielectric loss tangent (tan δ) versus frequency help in evaluating insulation

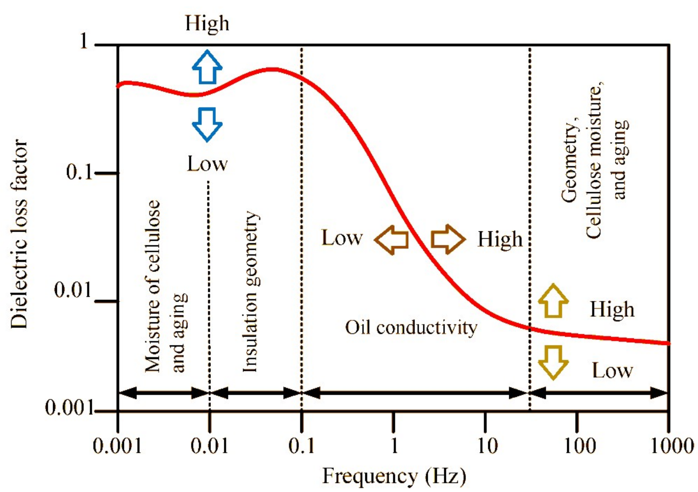


Figure 2. Electric strength rate as a function of emperature for different oil-paper composite insulation

Polarization and Depolarization Current (PDC) Analysis

PDC analysis evaluates the long-term behavior of oil-paper insulation by measuring its polarization and depolarization currents under a DC voltage. It provides insights into conductivity, moisture levels, and aging effects.

The polarization current $I_p(t)$ follows the relation:

$$I_p(t) = I_0 e^{-t/\tau}$$

where:

- I_0 is the initial current,
- τ is the relaxation time constant,
- t is time.

For a depolarization current $I_d(t)$, the discharge follows:

$$I_d(t) = -I_p(t)$$

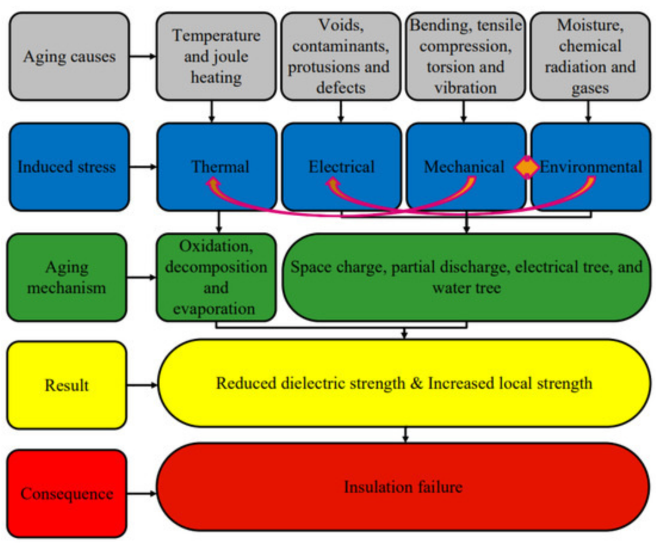


Figure 3. Experimental set up used o simulate oxygen influence on paper ageing.

Longer polarization times indicate aged insulation with higher moisture content. The charge retention capability of insulation is analyzed using these current decay patterns.

Methodology Graph:

A PDC graph showing current decay over time provides a clear picture of insulation aging trends.

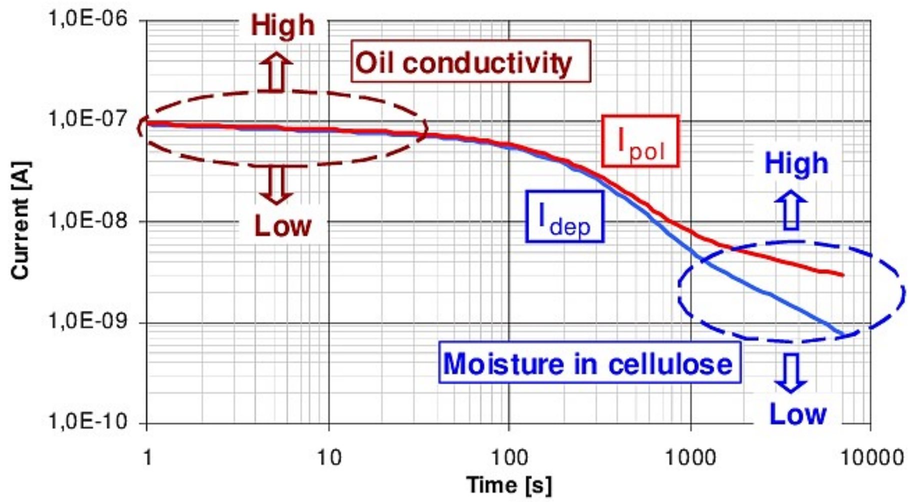


Figure 4. Dissipation factor rate as a function of emperature for different oil-paper composite insulation

3. Recovery Voltage Measurement (RVM)

Overview:

RVM evaluates the insulation condition by analyzing its voltage recovery after being charged. It provides information on the moisture level and insulation aging state.

Mathematical Basis:

The recovery voltage $V_r(t)$ follows an exponential equation:

$$V_r(t) = V_0 \left(1 - e^{-t/\tau}\right)$$

where:

- V_0 is the maximum recovery voltage,
- τ is the insulation time constant.

4. Dissolved Gas Analysis (DGA)

Overview:

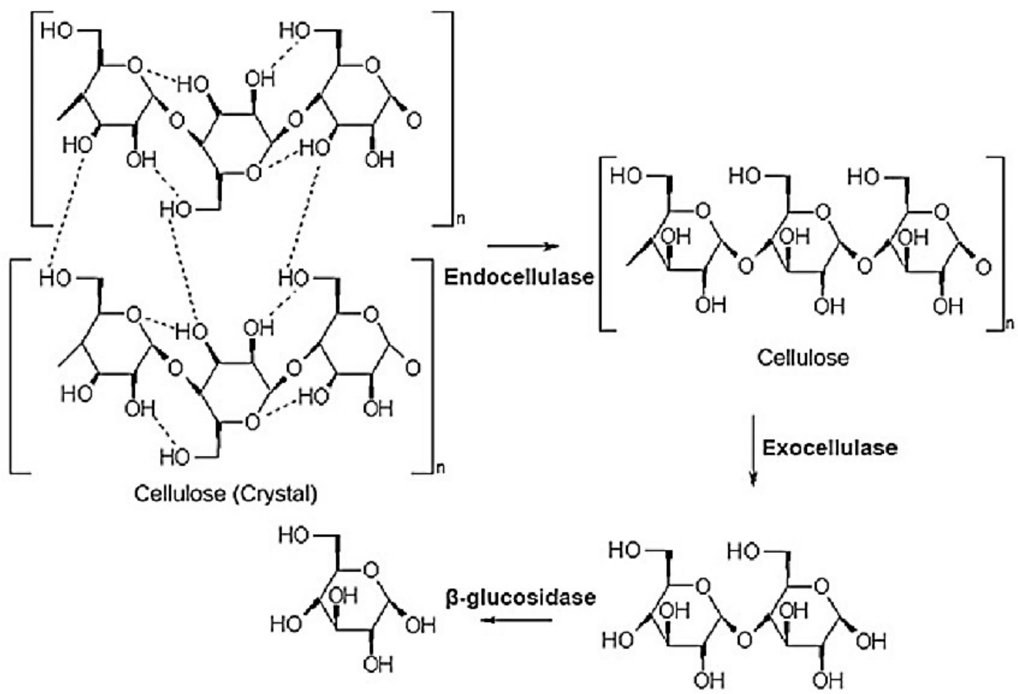
DGA is used to detect gas formation due to insulation degradation and thermal faults within transformers. It identifies key fault gases like hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), and carbon monoxide (CO).

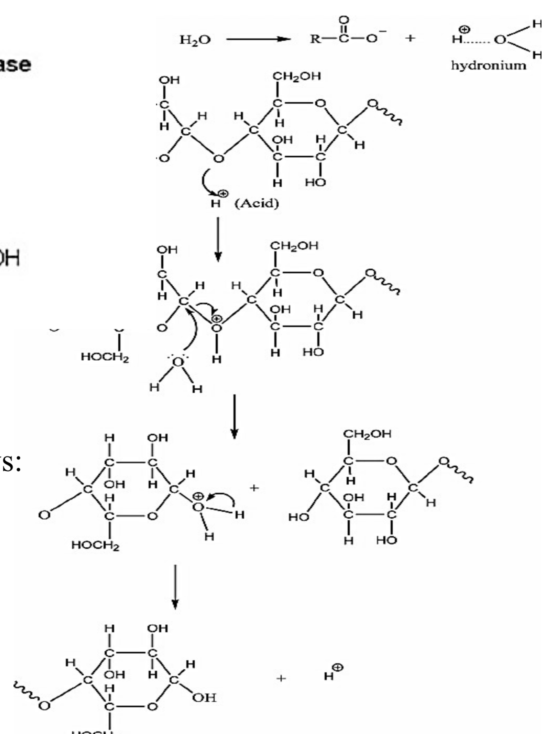
Mathematical Basis:

Gas formation follows Arrhenius-type degradation kinetics:

$$C = C_0 e^{-E_a/RT}$$

o ensure accuracy, findings from different studies were cross-referenced. Contradictory results were analyzed to determine variations in experimental conditions or material compositions. The methodology also included consultation of industrial standards and guidelines from organizations such as IEEE, CIGRÉ, and IEC to align the findings with practical transformer insulation requirements.This review methodology ensures a structured and comprehensive evaluation of the impact of aging byproducts on oil–paper insulation systems. By combining qualitative and quantitative analysis, cross-referencing data, and synthesizing solutions, this study provides a reliable foundation for further research and innovation in transformer insulation technology. (Yang et al., 2021).





Degree of Polymerization (DP) and Furfural Content

The relationship between furfural concentration and DP follows:

$$\log(C_{\text{fur}}) = a - b \times DP$$

where:

- C_{fur} = Furfural content in mg/L
- a, b = Empirical constants

This model is used to **estimate paper insulation aging** based on dissolved furfural levels.

4. Dielectric Response Techniques

Dielectric response techniques are advanced methods used to evaluate the condition of transformer insulation by analyzing its electrical behavior in response to an applied voltage. These techniques focus on measuring how the insulation reacts at different frequencies or voltages, providing a deeper understanding of its properties, including moisture content and aging. Below are the key dielectric response techniques:

- **4.1 Frequency Domain Spectroscopy (FDS)**
  Frequency Domain Spectroscopy (FDS) is a diagnostic method used to study the dielectric properties of transformer insulation materials by applying a range of AC voltage frequencies. This technique measures the complex impedance of the insulation system at different frequencies, providing insights into the characteristics of both the oil and the solid insulation (such as paper).
  - **Principle**: FDS works by applying an alternating current (AC) at varying frequencies and measuring the response of the insulation system, typically the phase shift and impedance. The dielectric properties of the insulation material, including its ability to store and dissipate electrical energy, are frequency-dependent. Changes in the dielectric response at specific frequencies provide valuable information about the insulation's health.
  - **Interpretation**: FDS is particularly useful in identifying moisture content, the degree of oil degradation, and the condition of the paper insulation. The response of the insulation to different frequencies can highlight shifts in its behavior due to aging or degradation. For example:
    - Low-frequency responses typically reflect the condition of the solid cellulose insulation (paper).
    - High-frequency responses are more sensitive to the condition of the transformer oil.
  - **Moisture Aging Correlation**: FDS is highly sensitive to the presence of moisture, as moisture alters the dielectric properties of both the paper and the oil. As moisture increases, the insulation system's impedance decreases, and the dielectric loss increases. By monitoring these changes, FDS can provide a direct correlation between moisture content and aging in the transformer insulation.
- **4.2 Polarization and Depolarization Current (PDC)**
  The Polarization and Depolarization Current (PDC) method involves applying a DC voltage to the insulation system and measuring the currents generated during

the polarization and depolarization phases. This technique offers insights into the condition of both the oil and solid insulation by assessing their response to DC stress.

- **Principle**: When a DC voltage is applied to the insulation, the charges in the insulation material polarize, aligning with the applied electric field. During the depolarization phase (when the voltage is removed), the material releases the stored charge, and the current is measured as the material depolarizes. The rate at which depolarization occurs is related to the degree of insulation degradation, moisture content, and the presence of aging byproducts. (Gao et al., 2023).
- **Interpretation**: The PDC method provides a time-dependent current measurement, which can be used to analyze the state of the insulation. A slower depolarization process typically indicates increased moisture content or deterioration of the solid insulation. Faster depolarization is usually associated with healthier insulation.
- **Moisture Aging Correlation**: As with FDS, PDC is sensitive to moisture levels in transformer insulation. Increased moisture content slows down the depolarization process, which can be detected by monitoring the depolarization current. This allows for early identification of moisture-related aging in the insulation system.

- **4.3 Dielectric Frequency Response (DFR)**

Dielectric Frequency Response (DFR) is a broader technique that includes both Frequency Domain Spectroscopy (FDS) and Polarization and Depolarization Current (PDC) methods, as it evaluates the dielectric properties of the insulation system over a range of frequencies.

- **Principles**: DFR involves measuring the impedance, dielectric loss, and phase angle of the insulation system across a spectrum of frequencies, from very low to high frequencies. The technique combines the information gathered from both the high-frequency and low-frequency responses of the insulation, providing a comprehensive view of the insulation's condition.
- **Interpretation**: DFR provides a detailed understanding of how the insulation behaves under varying electrical conditions. At low frequencies, DFR provides insight into the condition of the cellulose paper, while at higher frequencies, it gives information about the oil's condition. The overall dielectric response can highlight aging effects such as moisture absorption, oxidation, and the buildup of degradation byproducts.
- **Moisture Aging Correlation**: DFR is effective in correlating moisture content with aging in transformer insulation. Moisture significantly impacts the dielectric response, particularly at lower frequencies. By analyzing how the impedance and dielectric loss change with frequency, DFR can help assess the moisture levels in both the oil and paper insulation. Moisture in paper insulation leads to a decrease in the impedance and an increase in dielectric loss, which can be detected using DFR.

- **Temperature Correction and Influence**

Temperature plays a critical role in dielectric response techniques, as both the dielectric properties of insulation materials and the rate of aging are temperature-dependent. High temperatures accelerate aging, leading to an increase in moisture absorption, oxidation, and the formation of aging byproducts in the insulation system.

- **Temperature Correction**: Since dielectric properties are temperature-dependent, it is essential to correct for temperature variations when conducting measurements. Without temperature correction, the dielectric response data can be misinterpreted, leading to inaccurate conclusions about the condition of the insulation. Advanced software tools and correction factors are used to adjust the dielectric measurements for temperature effects, ensuring that the data is accurate and reliable.
- **Influence of Temperature**: Temperature influences the dielectric response in several ways. At higher temperatures, the viscosity of transformer oil decreases, allowing for faster moisture diffusion. This can result in an increased response to moisture content in dielectric measurements. Additionally, elevated temperatures accelerate the chemical aging of insulation, which can affect both the high- and low-frequency responses in techniques like FDS and DFR.

Dielectric response techniques such as FDS, PDC, and DFR provide invaluable data for assessing the health of transformer insulation systems. By carefully analyzing these responses, operators can identify aging mechanisms, moisture content, and other indicators of insulation degradation. Temperature correction is crucial in ensuring that these measurements reflect the true condition of the insulation, allowing for more accurate diagnoses and timely maintenance

MATHEMATICAL MODELING OF AGINGtINtLOW-TEMPERATURE CONDITIONS

Mathematical models help predict the aging behavior of oil-paper insulation by considering temperature-dependent parameters. Models such as:Arrhenius-based thermal aging models,Moisture migration models,Temperature-dependent dielectric relaxation modelsallow for better predictions of insulation life under low-temperature operating conditions. (Zhou et al., 2023). These models integrate real-time sensor data and laboratory testing results to provide a comprehensive understanding of aging mechanisms in cold climates.While significant progress has been made in understanding oil-paper insulation aging, several challenges remain:Limited Field Data: There is a lack of long-term field studies on oil-paper insulation performance in extremely cold climates.Need for Advanced Aging Models: Current mathematical models do not fully capture the combined effects of temperature, moisture, and electrical stress on insulation aging.Enhanced Condition Monitoring Techniques:

Mathematical Basis of FDS

FDS measures the dielectric permittivity **of** insulation over a range of frequencies to determine moisture content, conductivity, and degradation. The fundamental mathematical law governing FDS is Ohm's Law for complex impedance**:**

$$Z(\omega) = \frac{1}{j\omega C_0 \epsilon(\omega)}$$

where:

- $Z(\omega)$ = Impedance of the insulation system
- ω = Angular frequency $(2\pi f)$
- C_0 = Geometric capacitance of the insulation
- $\epsilon(\omega)$ = Complex permittivity, defined as:

A high **tan δ** indicates increased moisture and aging in insulation.

Example Calculation for FDS

Assume an oil-paper insulation sample has:

- $\epsilon' = 4.2$
- $\epsilon'' = 0.6$

The loss tangent is:

$$\tan\delta = \frac{0.6}{4.2} = 0.143$$

If the insulation exhibits $\tan\delta > 0.1$, it is considered aged and potentially unsafe for continued operation.

Mathematical Basis of PDC

PDC is based on **charge storage and decay** within insulation material when exposed to an applied voltage. It follows **exponential decay laws:**

$$I_p(t) = I_0 e^{-t/\tau}$$

where:

- $I_p(t)$ = Polarization current at time t
- I_0 = Initial polarization current
- τ = Time constant (related to insulation resistance and capacitance)

The **depolarization current** follows:

$$I_d(t) = -I_p(t)$$

This method helps assess moisture levels by measuring current retention in insulation.

Example Calculation for PDC

Given:

- $I_0 = 5 \times 10^{-9}$ A
- $\tau = 1000$ s
- $t = 2000$ s

$$I_p(2000) = 5 \times 10^{-9} e^{-2000/1000}$$

$$I_p(2000) = 5 \times 10^{-9} e^{-2}$$

Jsing $e^{-2} \approx 0.135$:

$$I_p(2000) = 5 \times 10^{-9} \times 0.135 = 0.675 \times 10^{-9} \text{ A}$$

Dissolved Gas Analysis (DGA) – Fault Gas Prediction

Mathematical Basis of DGA

DGA relies on gas evolution models using Arrhenius-type reaction kinetics, which describe the degradation rate of oil-paper insulation based on temperature and reaction energy:

$$C = C_0 e^{-E_a/RT}$$

where:

- C = Gas concentration at temperature T
- C_0 = Initial gas concentration
- E_a = Activation energy (J/mol)

$$\frac{C_2}{C_1} = e^{\frac{-120000}{8.314}\left(\frac{1}{323}-\frac{1}{293}\right)}$$

Computing the exponent:

$$\frac{1}{323} - \frac{1}{293} = -0.000334$$

$$\frac{-120000}{8.314} \times (-0.000334) = 4.83$$

$$C_2 = C_1 e^{4.83} = C_1 \times 125.8$$

Each diagnostic technique for oil-paper insulation follows well-defined mathematical principles. FDS relies on impedance and permittivity equations, PDC follows exponential charge decay laws, and DGA is governed by Arrhenius reaction kinetics. These mathematical foundations help quantify insulation aging, providing critical insights for transformer maintenance and reliability assessment.Advanced diagnostic techniques, modified insulating oils, and nanoparticle additives offer promising solutions for enhancing insulation performance.The integration of temperature-dependent aging models and real-time condition monitoring will play a crucial role in ensuring the longevity and reliability of transformers in cold climates. Future research should focus on developing low-temperature-specific insulation materials and improving diagnostic methodologies to address the challenges of oil-paper insulation aging in extreme environments. (Gao et al., 2023).

Methodology Step	**Description**	**Key Considerations**
1. Literature Search and Data Collection	Conducted an extensive search in academic databases such as IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar. Used relevant keywords related to oil–paper insulation aging and modifications.	- Focused on studies published between 2010–2024. - Included peer-reviewed journals, conference papers, and industry reports. - Ensured coverage of both theoretical and experimental studies.
2. Selection Criteria	Filtered collected literature based on relevance, credibility, and research methodology. Prioritized experimental studies, case studies, and comparative research.	- Selected studies focusing on aging effects, degradation mechanisms, and modifications. - Preferred papers with strong

		methodological frameworks. - Excluded studies lacking experimental data or specificity.
3. Data Analysis and Interpretation	Reviewed and categorized studies based on aging mechanisms, impact of aging byproducts, and modification techniques.	- Examined chemical and physical degradation processes. - Analyzed quantitative metrics like breakdown voltage, dielectric loss, and aging rate. - Compared performance improvements in modified insulation systems.
4. Synthesis of Challenges and Solutions	Identified common challenges in aging mitigation and synthesized potential solutions based on findings. Highlighted research gaps.	- Considered cost, implementation feasibility, and long-term stability. - Provided insights into emerging technologies such as nanomaterial-based insulation and ester oils.
5. Validation and Cross-Referencing	Cross-referenced findings from multiple sources to ensure reliability. Consulted industrial standards such as IEEE, CIGRÉ, and IEC for alignment with practical applications.	- Addressed conflicting study results by analyzing variations in experimental conditions. - Ensured alignment with real-world transformer insulation requirements.

Data Collection and Analysis

he data collection and analysis process for this review focuses on gathering relevant information from credible sources and systematically analyzing the impact of aging byproducts on modified insulation oil–paper systems. The approach includes identifying relevant studies, extracting key findings, and performing comparative analysis to evaluate challenges and solutions. (Yang et al., 2021).The data collection phase involved a systematic search and selection of relevant literature and experimental results.

Stage	Description	Key Considerations
Source Identification	Academic databases such as IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, Google Scholar, and technical reports from IEEE, CIGRÉ, and IEC.	- Focused on peer-reviewed journal articles, conference papers, and industrial reports. - Prioritized recent studies (2010–2024) but included foundational research.
Keyword Selection	Used keywords related to insulation aging, oil-paper degradation, aging byproducts, nanomaterial-enhanced insulation, and transformer maintenance.	- Ensured a comprehensive search using relevant keywords and Boolean operators. - Covered different modification strategies and aging factors.
Inclusion	Selected studies with experimental, simulation-	- Papers must include data on

Criteria	based, or field data on insulation degradation and improvement techniques.	dielectric breakdown voltage, moisture content, aging rates, or chemical byproducts. - Excluded studies lacking quantitative analysis or specificity.
Data Extraction	Extracted relevant information from selected studies, including experimental results, methodologies, and conclusions.	- Focused on comparative data between conventional and modified insulation systems. - Organized findings into key themes such as aging mechanisms, performance degradation, and mitigation strategies.

5. Partial Discharge and Acoustic Methods

Partial discharge (PD) is one of the most critical indicators of transformer insulation degradation. PD refers to localized electrical discharges within the insulation system that do not completely bridge the insulation, but still cause significant stress and degradation over time. These discharges often precede insulation failure, making their early detection crucial for maintaining the reliability of transformers. Acoustic methods are increasingly used to complement PD detection, as they allow for accurate localization and monitoring of PD activity. Below are the main techniques used for detecting and analyzing PD:

- **5.1 Offline and Online PD Measurement**
  - **Offline PD Measurement**:
    Offline partial discharge measurements are performed when the transformer is de-energized. This method involves the application of a test voltage to the transformer and measuring the PD activity. Offline testing provides a controlled environment where the transformer is taken offline, and its insulation can be evaluated without the risk of operational stress. This method allows for detailed analysis of PD characteristics, such as magnitude, frequency, and location. It is particularly useful for identifying the severity of PD in areas that are difficult to access during operation. Common offline PD measurement techniques include:
    - **PD Pulse Counting**: The number of PD pulses is counted during the test, and the discharge magnitude is measured.
    - **Phase Resolved PD Measurement**: The PD pulses are recorded across different phases to identify issues that may be specific to one phase or winding.
  - **Online PD Measurement**:
    Online PD measurement is performed while the transformer is energized, which allows for continuous monitoring during normal operation. This method detects partial discharge activity in real-time, making it ideal for early detection of faults before they cause catastrophic failure. Online PD measurement is typically done using sensors such as:

        - **High-Frequency Current Transformers (HFCT)**: These sensors detect PD-induced currents.
        - **UHF Sensors**: Ultra-high-frequency (UHF) sensors are used to detect PD signals in gas-insulated transformers or areas where conventional methods are ineffective.
        - **Capacitive Couplers**: These devices are connected to the transformer's bushings or other accessible parts to measure the PD signals.

  Online measurements allow for the detection of both high and low-frequency PD, which can help diagnose early insulation deterioration, and are useful for tracking PD activity over time. The advantage of online testing is that it enables continuous condition monitoring without the need for transformer shutdown, which is essential for ensuring long-term reliability.

- **5.2 Acoustic Emission for PD Location**
  Acoustic emission (AE) is a non-invasive technique that uses ultrasonic sensors to detect the sounds produced by partial discharges. These sounds are generated when PD occurs within the insulation material, creating micro-vibrations that propagate through the transformer housing and can be detected by specialized microphones or sensors.
    - **Principle**: Acoustic sensors placed on the transformer's outer surface capture the sound waves generated by PD activity. The frequency and intensity of the acoustic signals vary depending on the type of PD (e.g., corona, surface discharge, or internal arcing), and these signals can be analyzed to determine the location and severity of the discharges.
    - **PD Localization**: Acoustic emission is particularly valuable for locating the source of PD activity. By placing multiple sensors around the transformer and analyzing the time difference in the arrival of acoustic signals at each sensor, it is possible to triangulate the source of the partial discharge. This technique helps to identify the specific location of faults within the transformer, such as areas of insulation breakdown or void formation. This localization capability is especially useful in large, complex transformer systems where pinpointing the source of PD can be challenging with traditional methods.
    - **Advantages**: Acoustic emission offers several advantages:
        - **Real-Time Monitoring**: AE provides a real-time view of the transformer's condition, enabling quick response to emerging issues.
        - **Non-Invasive**: The method does not require disassembly or direct contact with the transformer's internal components.
        - **Sensitive to Early PD**: AE is particularly sensitive to low-level PD activity, which may not be detected by other methods, making it effective for early fault detection.
- **5.3 PD Activity Under Low-Temperature Conditions**
  Partial discharge activity can be influenced by temperature changes, including those caused by low-temperature operating conditions. Temperature affects the

electrical properties of both the transformer oil and solid insulation (paper), which in turn influences the occurrence and severity of PD. Understanding how PD behaves under low-temperature conditions is important for assessing transformer health, particularly in regions with extreme climates or during winter operations.

- **Impact of Low-Temperature Conditions**:
  At low temperatures, the dielectric strength of the insulation materials can improve, reducing the likelihood of PD. However, low temperatures can also introduce other factors that may increase the risk of PD:
  - **Increased Viscosity of Oil**: At lower temperatures, the transformer oil becomes more viscous, which can hinder its ability to dissipate heat and lead to localized hot spots. This, in turn, can create conditions conducive to PD.
  - **Moisture Freezing**: Moisture that may be present in the oil or paper insulation can freeze at low temperatures, which might cause internal stresses or cracks in the insulation, increasing the likelihood of PD.
  - **Voltage Stress**: If the transformer is exposed to rapid temperature changes or extreme cold, it can create mechanical stresses in the insulation, potentially leading to cracks or voids where PD can initiate.
- **PD Behavior Under Low Temperatures**:
  At low temperatures, partial discharge activity may be lower because the insulation materials are less conductive and more resistant to discharge. However, once the temperature rises and the insulation becomes more conductive or moisture rehydrates, PD activity can suddenly increase, often leading to sudden and severe faults. Monitoring PD under such conditions requires careful analysis of temperature-related impacts, as low-temperature testing may not fully reflect operational behavior during warmer periods.
- **Considerations for Low-Temperature Operation**:
  For transformers operating in cold climates, it is crucial to:
  - Continuously monitor PD activity under varying temperature conditions to understand how insulation materials respond to temperature fluctuations.
  - Implement thermal management strategies to prevent the oil from becoming overly viscous and ensure that the transformer maintains stable operation across a wide temperature range.
  - Regularly inspect and maintain moisture levels in the transformer to prevent freezing and internal stresses in the insulation.

This approach ensures that PD risks are minimized, and any potential insulation breakdowns due to low temperatures are detected early.

Partial discharge detection and localization are essential for transformer maintenance, helping to identify weaknesses in the insulation system before they lead to failure. By combining offline and online PD measurement techniques with acoustic emission methods, operators can gain a comprehensive understanding of the health of the transformer insulation. Monitoring PD activity under low-temperature conditions is also critical for ensuring that transformers continue to operate reliably in extreme climates. These techniques, when properly applied, enhance the ability to predict transformer failures and extend the lifespan of critical infrastructure.

ANALYSIS

Oil-paper insulation is a crucial component of power transformers and high-voltage electrical systems, providing excellent dielectric properties and mechanical strength. However, at low temperatures, its performance is significantly affected by various factors, including aging byproducts, moisture migration, changes in electrical conductivity, and mechanical stability. A comprehensive analysis of these factors is essential for understanding the reliability and long-term performance of oil-paper insulation in cold climates. (Gao et al., 2023).Aging byproducts play a significant role in the degradation of oil-paper insulation. The deterioration process is primarily driven by thermal, electrical, and environmental stresses, leading to the formation of acids, moisture, carbon oxides (CO and CO_2), and furanic compounds. These byproducts alter the insulation's dielectric properties and contribute to its mechanical weakening over time. At sub-zero temperatures, chemical reaction rates slow down, which in some cases delays oxidation and furan generation. However, moisture within the insulation system behaves differently, often condensing and freezing, which introduces new risks. Ice crystallization in moisture-laden insulation can cause physical expansion, leading to structural stress and micro-cracking in the cellulose fibers of the paper. These cracks, once formed, may allow more moisture to penetrate the insulation, accelerating degradation even at low temperatures. (Yang et al., 2021).The migration and distribution of moisture within oil-paper insulation are particularly concerning in cold environments. Moisture significantly influences the dielectric behavior of the insulation system, and its movement is governed by temperature gradients. At low temperatures, moisture tends to accumulate in the paper layers, where it may freeze and alter the mechanical and electrical properties of the insulation. This moisture accumulation increases the risk of partial discharge activity and dielectric breakdown, especially if the insulation system is exposed to repeated freeze-thaw cycles. Additionally, the permittivity of insulation materials changes with temperature, which affects charge carrier mobility and overall dielectric strength. Studies have shown that breakdown voltage tends to decrease at temperatures below -20°C in moisture-laden insulation, making transformers more vulnerable to electrical failures in extreme cold.Another critical factor affecting the performance of oil-paper insulation at low temperatures is its electrical conductivity. The conductivity of insulation materials depends on ion mobility, which is temperature-sensitive.

Comparative Performance Analysis of Insulation Oils

The table below presents a comparative analysis of different insulation oils based on key performance parameters:

Parameter	**Mineral Oil**	**Ester-Based Oil**	**Nanoparticle-Enhanced Oil**
Dielectric Strength	Moderate (Decreases with aging)	High (Less affected by moisture)	Very High (Enhanced with nanoparticles)
Moisture Absorption	High (Degrades insulation paper)	Very High (Retains moisture without significant impact)	Moderate (Nanoparticles slow moisture impact)
Thermal Stability	Low (Aging accelerates at high temperatures)	High (Withstands high temperatures better)	High (Nanoparticles enhance thermal properties)
Oxidation Resistance	Low (Rapid acid formation)	High (Contains natural antioxidants)	Very High (Enhanced with synthetic antioxidants)
Sludge Formation	High (Reduces cooling efficiency)	Low (Less sludge formation)	Very Low (Nanoparticles prevent deposits)
Longevity	Short (Requires frequent monitoring)	Long (Better aging resistance)	Long (Improved performance over time)

This comparative analysis highlights that ester-based and nanoparticle-enhanced oils outperform conventional mineral oils in terms of dielectric strength, oxidation resistance, and longevity. However, both modified oils present challenges in terms of cost, dispersion stability (for nanoparticles), and maintenance requirements.The lack of established industry standards for modified insulation oils poses a challenge for large-scale implementation.Regulatory bodies such as IEEE, IEC, and CIGRE need to establish guidelines for evaluating the performance and safety of these new insulation technologies.Field studies and long-term operational data are essential for convincing manufacturers and utilities to adopt modified insulation solutions.Based on the analysis, future research should focus on:Improving cost-effective nanoparticle synthesis and dispersion techniques to enhance oil stability and performance.Hybrid insulation solutions, such as combining nanoparticle-enhanced esters, to optimize dielectric and thermal properties.Developing smart monitoring systems to track real-time insulation aging and optimize maintenance schedules.Field validation studies to establish performance benchmarks and gain industry acceptance.This analysis highlights the significant impact of aging byproducts on insulation oil–paper systems and the potential benefits of modified insulation solutions. Nanoparticle-enhanced and ester-based oils offer superior aging resistance, thermal stability, and dielectric performance compared to conventional mineral oils. However, challenges related to cost, compatibility, and regulatory approvals must be addressed before widespread adoption. Future research should focus on cost optimization, hybrid insulation approaches, and real-world field validation to ensure long-term reliability and efficiency in transformer insulation systems.

6. Advanced and Emerging Techniques

As transformer insulation technology evolves, new diagnostic techniques and materials are being developed to enhance performance and reliability. These advanced methods enable earlier fault detection, more accurate diagnostics, and better overall management of transformer health. Below are some of the emerging techniques in transformer insulation monitoring:

- **6.1 Optical Fiber and Embedded Sensors**
  - **Principle**: Optical fiber sensors (OFS) are increasingly used in transformer insulation systems due to their ability to measure various parameters such as temperature, moisture, pressure, and strain with high accuracy. These sensors work by detecting changes in light transmission or scattering caused by physical or chemical changes in the insulation material.
  - **Applications**:
    - **Temperature and Strain Monitoring**: Optical fibers embedded in insulation materials can provide real-time data on the internal temperature and mechanical stress within the transformer. This helps detect areas that are susceptible to thermal degradation or mechanical failure.
    - **Moisture Detection**: Changes in moisture content within the insulation can be detected by optical fiber sensors that monitor changes in light properties.
    - **Advantages**: Optical fiber sensors are immune to electromagnetic interference, have high spatial resolution, and can provide continuous, real-time monitoring over long distances.
- **6.2 Frequency Response Analysis (FRA)**
  - **Principle**: Frequency Response Analysis (FRA) is a diagnostic technique used to assess the mechanical integrity and electrical properties of transformer windings. It works by applying an AC signal across a frequency range and analyzing the resulting response to detect any mechanical or electrical faults within the transformer.
  - **Applications**:
    - **Winding Deformation**: FRA is particularly useful for identifying winding deformation, core faults, or short circuits within the transformer. By analyzing how the frequency response changes over time, engineers can detect shifts in impedance caused by winding movements or insulation breakdowns.
    - **Advantages**: FRA provides detailed insight into the internal condition of the transformer without the need for disassembly or downtime. It allows for early detection of issues before they escalate into catastrophic failures.

- **6.3 Infrared Thermography**
  - **Principle**: Infrared thermography involves using thermal cameras to detect temperature variations on the surface of transformer components. This method is based on the principle that different materials and components will exhibit distinct thermal signatures depending on their condition and performance.
  - **Applications**:
    - **Hotspot Detection**: Thermal imaging can identify hotspots or areas of high temperature within the transformer, indicating potential overheating or insulation degradation.
    - **External Monitoring**: Infrared thermography is non-invasive and can be performed while the transformer is in operation, allowing for real-time monitoring of critical components such as bushings, bushings, tap changers, and cooling systems.
    - **Advantages**: Infrared thermography provides a fast, non-destructive means of identifying hot spots and potential fault areas, reducing the risk of failure and improving preventive maintenance practices.
- **6.4 Nanofluids and Smart Materials**
  - **Principle**: Nanofluids are engineered fluids that incorporate nanoparticles to improve the thermal, electrical, and mechanical properties of the insulating medium. These fluids can provide enhanced performance compared to conventional oils.
  - **Applications**:
    - **Improved Cooling and Thermal Conductivity**: Nanofluids can enhance the cooling properties of transformer oil, improving heat dissipation and reducing the risk of overheating.
    - **Smart Materials**: Smart materials, such as shape-memory polymers and piezoelectric materials, can be integrated into transformer insulation systems to monitor and respond to mechanical stresses and temperature changes.
    - **Advantages**: Nanofluids and smart materials offer improved performance, increased efficiency, and greater durability of transformer insulation systems. They can also contribute to more effective monitoring and diagnostic capabilities.
- **6.5 AI, ML, and Data Fusion Diagnostics**
  - **Principle**: Artificial intelligence (AI) and machine learning (ML) are transforming the way transformer insulation health is assessed. By combining AI algorithms and data from various diagnostic tools, transformers can be continuously monitored, and potential faults can be predicted with high accuracy.
  - **Applications**:
    - **Fault Prediction**: AI and ML models can analyze data from DGA, PD measurement, temperature sensors, and other diagnostic

techniques to predict potential transformer failures before they occur.

- **Data Fusion**: Data fusion integrates information from multiple sensors and diagnostic methods, such as DGA, temperature monitoring, and acoustic sensors, to provide a comprehensive understanding of transformer health.
- **Advantages**: AI and ML can improve the precision of transformer diagnostics, reduce false positives, and optimize maintenance schedules. These technologies enable more proactive asset management by providing early warning signs of failure.

7. Low-Temperature Performance of Insulation

Transformers are often exposed to a wide range of environmental conditions, including low temperatures, which can significantly impact their performance and longevity. Understanding how insulation materials behave under low-temperature conditions is essential for ensuring transformer reliability in cold climates. The following sections highlight the challenges, research findings, diagnostic implications, and innovations related to low-temperature performance:

- **7.1 Challenges in Cold Climates**
  - **Oil Viscosity Increase and Reduced Convection**:
    At low temperatures, transformer oils become more viscous, which reduces the ability of the oil to circulate effectively within the transformer. This leads to poor heat dissipation, potentially causing localized overheating and insulation stress. In extreme cold, the reduced convection in the oil can significantly impact the transformer's cooling system, leading to potential damage.
  - **Paper Brittleness and Accelerated Cracking Risk**:
    Cellulose-based paper insulation becomes brittle at low temperatures, increasing the risk of cracks or fractures in the paper, which can lead to insulation breakdown. Over time, this brittleness can cause insulation failure, especially when mechanical stresses are applied during transformer operation.
  - **Moisture Migration Under Freezing Conditions**:
    Moisture that is present in the oil or solid insulation can migrate and freeze at low temperatures. Freezing moisture can cause internal stresses, reducing the dielectric strength of the insulation and increasing the risk of partial discharge and insulation degradation.
  - **Influence on Dielectric Measurements**:
    Low temperatures can affect dielectric measurement techniques, such as Frequency Domain Spectroscopy (FDS), Polarization and Depolarization Current (PDC), and Partial Discharge (PD) testing. Temperature-induced changes in the dielectric properties of the insulation materials can lead to

inaccurate readings, making it difficult to assess the true condition of the transformer insulation.

- **7.2 Research Findings**
  - **Behavior of Mineral vs Ester Oils at Low Temperatures**: Mineral oils and ester-based oils behave differently at low temperatures. Ester oils tend to maintain better low-temperature fluidity compared to mineral oils, which means they offer superior performance in colder climates. Research has shown that ester oils are less likely to become overly viscous and can maintain better thermal conductivity at sub-zero temperatures.
  - **FDS/PDC Testing Under Temperature-Controlled Environments**: Studies have been conducted on the behavior of insulation systems under low temperatures using temperature-controlled environments for FDS and PDC testing. These studies help to determine how insulation materials respond to cold temperatures and how to adjust testing methods for more accurate results in low-temperature conditions.
  - **Use of Thermally Upgraded Papers and Nanofluids**: Research has focused on the use of thermally upgraded papers and nanofluids in transformers operating in cold regions. Thermally upgraded papers are more resilient to temperature fluctuations, and nanofluids provide better cooling performance, which is crucial for transformer reliability in extreme climates.
  - **Field Performance Data from Cold Regions**: Performance data from transformers in cold regions like Canada, Scandinavia, and Russia have been analyzed to assess the long-term impact of low temperatures on transformer insulation. These data provide valuable insights into the operational challenges and failure modes of transformers in such environments.
- **7.3 Diagnostic Implications**
  - **Need for Temperature Correction Models**: To accurately assess transformer insulation health in cold climates, temperature correction models are necessary. These models adjust diagnostic readings to account for temperature-induced changes in the electrical properties of insulation materials.
  - **Risk of Under- or Over-Estimating Insulation Health**: Without proper temperature compensation, diagnostic techniques may under- or overestimate the health of the insulation. This can lead to false conclusions regarding transformer condition, potentially causing unnecessary repairs or leaving critical issues undetected.
  - **Advances in Temperature-Compensated Diagnostic Tools**: Recent advancements in diagnostic tools have focused on incorporating temperature correction algorithms to improve the accuracy of results in cold environments. These tools allow for real-time monitoring of

transformer health while considering temperature-induced changes in the insulation.

- **7.4 Design and Material Innovations**
  - **Low-Temperature Tested Insulating Fluids**: New insulating fluids have been developed that maintain better performance at low temperatures. These fluids are designed to reduce viscosity changes and maintain better dielectric properties, even under extreme cold.
  - **Insulation Systems Tailored for Arctic/Sub-Zero Applications**: Innovations in insulation system design have led to the development of transformer insulation systems specifically tailored for use in arctic or sub-zero environments. These systems use advanced materials, improved cooling techniques, and low-temperature-resistant fluids to ensure transformer reliability in extreme climates.

By understanding the challenges posed by low temperatures and integrating these innovations into transformer design and maintenance practices, operators can ensure that their equipment performs reliably in cold climates and operates at optimal efficiency.

8. Comparative Evaluation of Techniques

The comparison below evaluates the various diagnostic techniques used in assessing the health of transformer insulation systems. It considers what each method detects, its environmental sensitivity, accuracy, ease of use, cost, field applicability, and suitability for cold environments.

Technique	What it Detects	Environmental Sensitivity	Accuracy	Ease of Use	Cost	Field Applicability	Suitability for Cold Environments
Dissolved Gas Analysis (DGA)	Gas formation due to thermal/electrical stresses (e.g., CO, CO_2, CH_4, C_2H_2)	Sensitive to temperature and moisture variations	High, if properly calibrated	Moderate; requires sample extraction	Moderate	Widely used in operational environments	Reduced sensitivity at extreme cold
Furan Analysis	Degradation of cellulose paper (furans)	Less affected by environmental conditions	High	Moderate; lab-based	Moderate	Lab-based, requires oil extraction	Not affected by cold directly
Moisture Measurement (Karl Fischer, etc.)	Moisture content in oil and solid insulation	Sensitive to humidity, moisture migration in cold	High	Moderate to easy	Moderate	Can be performed on-site	Cold can cause migration challenges
IR and PI	Thermal performance, insulation	Sensitive to temperature changes	Moderate to high	Easy, especially IR	Low to moderate	Quick field testing for thermal	Temperature changes impact

	integrity (polarization index)	and moisture		thermography		anomalies	accuracy
Recovery Voltage Measurement (RVM)	Insulation condition based on recovery voltage behavior	Affected by temperature and moisture content	Moderate	Moderate to difficult	High	Limited field use, requires special setup	Cold temperature affects results
Frequency Domain Spectroscopy (FDS)	Insulation dielectric properties, moisture and aging effects	Highly sensitive to temperature and moisture	High	Moderate	High	Lab-based but can be field-adapted	Temperature correction required
Polarization and Depolarization Current (PDC)	Insulation moisture content and degradation	Sensitive to temperature and aging	High	Moderate to difficult	High	Lab-based, but can be adapted to field	Temperature-sensitive results
Partial Discharge (PD)	Discharges within the insulation due to breakdown	Sensitive to humidity and temperature	High	Moderate to easy	High	Widely used, can be online or offline	Low temp impacts PD behavior
Optical Fiber Sensors	Temperature, strain, moisture, pressure	Not affected by environmental factors like humidity	Very high	Easy, once installed	High	Requires installation, useful for real-time monitoring	Performs well in cold, immune to interference
Infrared Thermography	Surface temperature variations, hotspots	Affected by ambient temperature, snow, and moisture	High	Easy	Moderate	Widely used for surface diagnostics	Impacted by extreme cold weather
Nanofluids and Smart Materials	Thermal conductivity, mechanical stress, moisture resistance	Immune to external environmental factors like humidity	Moderate	Easy to moderate	High	Emerging field, not widely deployed	Potentially useful in cold climates

9. Challenges and Limitations

As transformer diagnostics become more advanced, several challenges and limitations persist in ensuring these methods are accurate and widely applicable:

- **Data Interpretation and Standardization Issues**:
  Many diagnostic techniques generate large amounts of data that require expert interpretation. There is a lack of standardization in the industry, making it

difficult to compare results across transformers or diagnostic methods. The absence of universally accepted thresholds for interpretation also complicates the diagnostic process.

- **Cost and Complexity of Advanced Diagnostics**:
  Advanced techniques such as optical fiber sensors, AI/ML models, and Frequency Domain Spectroscopy (FDS) can be expensive, both in terms of initial installation and maintenance. These methods often require specialized equipment and skilled personnel to interpret the data. Small and medium-sized utilities may struggle to afford or implement such sophisticated diagnostics.
- **Limited Field Data for Newer Methods**:
  Emerging diagnostic methods, such as AI-based systems or nanofluids, are still in their early stages. Limited field data available for these techniques makes it difficult to assess their effectiveness and reliability over time, especially in real-world, cold-environment scenarios.
- **Environmental Impacts (Humidity, Cold, etc.)**:
  Environmental conditions such as high humidity or extreme cold can adversely affect the performance and accuracy of diagnostic techniques. For instance, moisture migration in insulation systems during freezing temperatures can lead to false readings, and cold temperatures can affect fluid viscosity, making certain techniques less reliable in cold climates.

10. Future Directions

As transformer insulation technology evolves, several key directions are shaping the future of transformer diagnostics:

- **Real-Time, Environment-Aware Diagnostic Systems**:
  Future diagnostic systems will leverage real-time data from multiple sensors and environmental conditions to provide dynamic, environment-aware insights into transformer health. These systems will incorporate artificial intelligence to adapt diagnostic thresholds based on factors like ambient temperature and humidity, making monitoring more accurate and proactive.
- **Digital Twins with Thermal Behavior Modeling**:
  Digital twins of transformer insulation systems will become more common, providing a virtual replica of the transformer that can simulate thermal and aging behaviors under various conditions. This will enable better prediction of failures and maintenance needs, allowing for more effective management of transformer health, especially under extreme environmental conditions.
- **Smarter Moisture/Oil Aging Models**:
  Advances in modeling software will enable the development of smarter moisture and oil aging models that consider temperature, load, and operational stress factors. These models will help predict the future performance of insulation materials with greater accuracy, especially under extreme temperature conditions.

- **Industry-Wide Cold-Climate Performance Testing Standards**:
  As the importance of transformer performance in cold climates grows, there is a pressing need for standardized testing procedures that assess transformer insulation systems under low-temperature conditions. Such standards will ensure that transformers are designed and tested for reliable operation in harsh climates, helping to minimize failures in cold regions.
- **Material Innovation for Resilient Insulation Systems**:
  Ongoing research into new materials, such as thermally upgraded papers, nanofluids, and smart materials, will lead to more resilient insulation systems capable of withstanding extreme temperatures and stresses. These materials will improve transformer reliability, reduce the risk of insulation degradation, and extend the lifespan of transformer assets.

CONCLUSIONS:

The performance of oil-paper insulation in power transformers is significantly influenced by low-temperature conditions, which introduce unique challenges related to moisture migration, dielectric properties, and mechanical stability. (Gao et al., 2023). While traditional aging models focus primarily on thermal degradation, low-temperature environments slow down certain chemical reactions but exacerbate other issues such as moisture condensation, increased brittleness, and altered charge carrier mobility. The presence of ice crystals within insulation paper can lead to physical expansion, causing internal stress and micro-cracks that accelerate overall degradation. Additionally, temperature fluctuations create thermal stresses at the oil-paper interface, increasing the likelihood of partial discharges and insulation failure. These findings emphasize the need for a more detailed understanding of how cold environments affect insulation performance to ensure the long-term reliability of transformers operating in such conditions.To address these challenges, various diagnostic techniques, including Frequency Domain Spectroscopy (FDS), Polarization and Depolarization Current (PDC) analysis, Recovery Voltage Measurement (RVM), and Dissolved Gas Analysis (DGA), have been explored for assessing insulation health under low-temperature conditions. However, the accuracy of these techniques is affected by changes in moisture distribution and dielectric behavior at sub-zero temperatures, necessitating modified analytical approaches. Moreover, mathematical models must be refined to account for low-temperature effects on insulation aging, incorporating factors such as moisture redistribution dynamics, permittivity variations, and mechanical stress accumulation. (Yang et al., 2021). Advanced transformer monitoring systems that integrate AI-based predictive maintenance strategies can further improve insulation condition assessment, allowing for early detection of degradation and minimizing unexpected failures.Future advancements in insulation technology will play a crucial role in mitigating the effects of low temperatures on oil-paper systems. Cold-resistant insulating oils with improved viscosity characteristics, nano-dielectric additives, and enhanced cellulose insulation materials offer promising solutions for improving insulation performance in extreme climates. Additionally, more effective moisture removal techniques, such as advanced vacuum drying and sorbent filtration systems, can help maintain the integrity of oil-paper insulation over extended operational lifespans.

REFERENCES

- Jin, L.; Kim, D.; Abu-Siada, A.; Kumar, S. Oil-Immersed Power ransformer Condition Monitoring Methodologies: A Review. *Energies* **2022**, *15*, 3379. [**Google Scholar**] [**CrossRef**]
- Bracale, A.; Carpinelli, G.; Pagano, M.; De Falco, P. A Probabilistic Approach for Forecasting he Allowable Current of Oil-Immersed ransformers. *IEEE rans. Power Del.* **2018**, *33*, 1825–1834. [**Google Scholar**] [**CrossRef**]
- Christina, A.J.; Salam, M.A.; Rahman, Q.M.; Wen, F.; Ang, S.P.; Voon, W. Causes of ransformer failures and diagnostic methods—A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1442–1456. [**Google Scholar**]
- Foros, J.; Istad, M. Health Index, Risk and Remaining Lifetime Estimation of Power ransformers. *IEEE rans. Power Del.* **2020**, *35*, 2612–2620. [**Google Scholar**] [**CrossRef**] [**Green Version**]
- N'cho, J.S.; Fofana, I.; Hadjadj, Y.; Beroual, A. Review of Physicochemical-Based Diagnostic echniques for Assessing Insulation Condition in Aged ransformers. *Energies* **2016**, *9*, 367. [**Google Scholar**] [**CrossRef**]
- Area, M.C.; Ceradame, H. Paper aging and degradation: Recent findings and research methods. *Bioresources* **2011**, *6*, 5307–5337. [**Google Scholar**]
- Okabe, S.; Ueta, G.; suboi, . Investigation of aging degradation status of insulating elements in oil-immersed ransformer and its diagnostic method based on field measurement data. *IEEE rans. Dielectr. Electr. Insul.* **2013**, *20*, 346–355. [**Google Scholar**] [**CrossRef**]
- Zhang, E.; Zheng, H.; Zhang, C.; Wang, J.; Shi, K.; Guo, J.; Schwarz, H.; Zhang, C. Aging state assessment of ransformer cellulosic paper insulation using multivariate chemical indicators. *Cellulose* **2021**, *28*, 2445–2460. [**Google Scholar**] [**CrossRef**]
- Li, J.; Zhang, J.; Wang, F.; Huang, Z.; Zhou, Q. A novel aging indicator of ransformer paper insulation based on dispersion staining colors of cellulose fibers in oil. *IEEE Electr. Insul. Mag.* **2018**, *34*, 8–16. [**Google Scholar**] [**CrossRef**]
- Emsley, A.M.; Stevens, G.C. Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled ransformers. *IEE Proc. Sci. Meas. echol.* **1994**, *141*, 324–334. [**Google Scholar**] [**CrossRef**]
- Du, D.; ang, C.; Zhang, J.; Hu, D. Effects of hydrogen sulfide on he mechanical and hermal properties of cellulose insulation paper: A molecular dynamics simulation. *Mater. Chem. Phys.* **2020**, *240*, 122153. [**Google Scholar**] [**CrossRef**]
- Wise, L.D. *Wood Chemistry*; Reinhold Publishing Co.: New York, NY, USA, 1946. [**Google Scholar**]
- Zhou, Y.; Chen, W.; Yang, D.; Zhang, R. Raman spectrum characteristics and aging diagnosis of oil-paper insulation with different oil-paper ratios. *IEEE rans. Dielectr. Electr. Insul.* **2020**, *27*, 1587–1594. [**Google Scholar**] [**CrossRef**]
- Emsley, A.M.; Heywood, R.J.; Ali, M.; Xiao, X. Degradation of cellulosic insulation in power ransformers. Part 4: Effects of ageing on he ensile strength of paper. *IEE Proc. Sci. Meas. echnol.* **2000**, *147*, 285–290. [**Google Scholar**] [**CrossRef**]
- Hill, D.J.T.; Le, .T.; Darveniza, M.; Saha, . A study of degradation of cellulosic insulation materials in a power ransformer. Part 2: ensile strength of cellulose insulation paper. *Polym. Degrada. Stabil.* **1995**, *49*, 429–435. [**Google Scholar**] [**CrossRef**]

- Ariannik, M.; Razi-Kazemi, A.A.; Lehtonen, M. An approach on lifetime estimation of distribution ransformers based on degree of polymerization. *Reliab. Eng. Syst. Saf.* **2020**, *198*, 106881. [**Google Scholar**] [**CrossRef**]
- Lundgaard, L.E.; Hansen, W.; Linhjell, D.; Painter, .J. Aging of oil-impregnated paper in power ransformers. *IEEE rans. Power Deliv.* **2004**, *19*, 230–239. [**Google Scholar**] [**CrossRef**]
- Shroff, D.H.; Stannett, A.W. A review of paper aging in power ransformers. *Gener. ransm. Distrib. IEE Proc. C* **1985**, *132*, 312–319. [**Google Scholar**] [**CrossRef**]
- Force, C.T. *Ageing of Cellulose in Mineral-Oil Insulated ransformers*; CIGRE: Paris, France, 2007. [**Google Scholar**]
- Sana, .K. Review of modem diagnostic echniques for assessing insulation condition in aged ransformers. *IEEE rans. Dielectr. Electr. Insul.* **2003**, *10*, 903–917. [**Google Scholar**]
- Saha, .K.; Purkait, P. Investigations of emperature Effects on he Dielectric Response Measurements of ransformer Oil-Paper Insulation System. *IEEE rans. Power Deliv.* **2008**, *23*, 252–260. [**Google Scholar**] [**CrossRef**]
- Emsley, A.M. he kinetics and mechanisms of degradation of cellulosic insulation in power ransformers. *Polym. Degrada. Stabil.* **1994**, *44*, 343–349. [**Google Scholar**] [**CrossRef**]
- Emsley, A.M.; Xiao, X.; Heywood, R.J.; Ali, M. Degradation of cellulosic insulation in power ransformers. Part 2: Formation of furan products in insulating oil. *IEE Proc. Sci. Meas. echol.* **2000**, *147*, 110–114. [**Google Scholar**] [**CrossRef**]
- Behjat, V.; Emadifar, R.; Pourhossein, M.; Rao, U.M.; Fofana, I.; Najjar, R. Improved Monitoring and Diagnosis of ransformer Solid Insulation Using Pertinent Chemical Indicators. *Energies* **2021**, *14*, 3977. [**Google Scholar**] [**CrossRef**]
- Matharage, S.Y.; Liu, Q.; Wang, Z.D. Aging assessment of kraft paper insulation hrough methanol in oil measurement. *IEEE rans. Dielectr. Electr. Insul.* **2016**, *23*, 1589–1596. [**Google Scholar**] [**CrossRef**]
- Oommen, .V.; Prevost, .A. Cellulose insulation in oil-filled power ransformers: Part II maintaining insulation integrity and life. *IEEE Electr. Insul. Mag.* **2006**, *22*, 5–14. [**Google Scholar**] [**CrossRef**]
- Burton, P.J.; Graham, J.; Hall, A.C.; Laver, J.A.; Oliver, A.J. *Recent Developments by CEGB o Improve he Prediction and Monitoring of ransformer Performance*; CIGRE: Paris, France, 1984; Volume 30, p. 1209. [**Google Scholar**]
- Oria, C.; Ortiz, A.; Ferreño, D.; Carrascal, I.; Fernández, I. State-of-the-art review on he performance of cellulosic dielectric materials in power ransformers: Mechanical response and ageing. *IEEE rans. Dielectr. Electr. Insul.* **2019**, *26*, 939–954. [**Google Scholar**] [**CrossRef**]
- Rao, U.M.; Fofana, I.; Jaya, .; Rodriguez-Celis, E.M.; Jalbert, J.; Picher, P. Alternative Dielectric Fluids for ransformer Insulation System: Progress, Challenges, and Future Prospects. *IEEE Access* **2019**, *7*, 184552–184571. [**Google Scholar**]
- Ueta, G.; suboi, .; Okabe, S.; Amimoto, . Study on degradation causing components of various characteristics of ransformer insulating oil. *IEEE rans. Dielectr. Electr. Insul.* **2012**, *19*, 2216–2224. [**Google Scholar**] [**CrossRef**]
- Feng, D.; Hao, J.; Liao, R.; Chen, X.; Cheng, L.; Liu, M. Comparative Study on he hermal-Aging Characteristics of Cellulose Insulation Polymer Immersed in New hree-Element Mixed Oil and Mineral Oil. *Polymers* **2019**, *11*, 1292. [**Google Scholar**] [**CrossRef**] [**Green Version**]
- Łojewska, J.; Miśkowiec, P.; Łojewski, .; Proniewicz, L.M. Cellulose oxidative and hydrolytic degradation: In situ FTIR approach. *Polym. Degrada. Stabil.* **2005**, *88*, 512–520. [**Google Scholar**] [**CrossRef**]
- CIGRE Working Group. *Ageing of Liquid Impregnated Cellulose for Power ransformers*; CIGRE: Paris, France, 2018; Volume 1, p. 53. [**Google Scholar**]

- Lelekakis, N.; Wenyu, G.; Martin, D.; Wijaya, J.; Susa, D. A field study of aging in paper-oil insulation systems. *IEEE Electr. Insul. Mag.* **2012**, *28*, 12–19. [**Google Scholar**] [**CrossRef**]
- Cheim, L.; Platts, D.; Prevost, .; Xu, S. Furan analysis for liquid power ransformers. *IEEE Electr. Insul. Mag.* **2012**, *28*, 8–21. [**Google Scholar**] [**CrossRef**]
- Chen, L.; Liao, Y.; Guo, Z.; Cao, Y.; Ma, X. Products distribution and generation pathway of cellulose pyrolysis. *J. Clean. Prod.* **2019**, *232*, 1309–1320. [**Google Scholar**] [**CrossRef**]
- Usino, D.O.; Ylitervo, P.; Pettersson, A.; Richards, . Influence of emperature and ime on initial pyrolysis of cellulose and xylan. *J. Anal. Appl. Pyrol.* **2020**, *147*, 104782. [**Google Scholar**] [**CrossRef**]
- Lin, Y.C.; Cho, J.; ompsett, G.A.; Westmoreland, P.R.; Huber, G.W. Kinetics and mechanism of cellulose pyrolysis. *J. Phys. Chem. C* **2009**, *113*, 20097–20107. [**Google Scholar**] [**CrossRef**]
- Margutti, S.; Conio, G.; Calvini, P.; Pedemonte, E. Hydrolytic and oxidative degradation of paper. *Restaurator* **2001**, *22*, 67–83. [**Google Scholar**] [**CrossRef**]
- Ese, M.H.G.; Liland, K.B.; Lundgaard, L.E. Oxidation of paper insulation in ransformers. *IEEE rans. Dielectr. Electr. Insul.* **2010**, *17*, 939–946. [**Google Scholar**] [**CrossRef**]