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Research on Monitoring Technology for Insulation State of Distribution Transformer Winding Based on Finite Element Analysis

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Abstract

This study aims to optimize the insulation state monitoring technology of distribution transformer winding through finite element analysis （FEA） to improve the operation safety and life of power equipment. The paper firstly establishes the coupling simulation model of transformer winding and analyzes the insulation performance under different working conditions. Through simulation data analysis, the key factors affecting insulation aging and the characteristic model of insulation deterioration are constructed. In addition, the research also discusses the application of big data and artificial intelligence in the monitoring technology, which provides a new idea for the intelligent monitoring and optimization of the transformer insulation state. This study not only provides a new technical means for insulation state monitoring, but also provides theoretical support and technical basis for the reliable operation and life extension of power equipment.

Keywords: *Finite Element Analysis （FEA）, Distribution Transformer, Winding Insulation, Electric Field Simulation.*

Introduction

With the ongoing development of power systems, distribution transformers have become essential components of the grid, and their operational conditions significantly affect the safety and stability of the electrical network. The winding insulation is a critical part of transformers, and its condition is crucial for both their lifespan and performance [1]. Nonetheless, the cumulative effects of thermal aging, mechanical stress, and electrical stress from extended operation can lead to the deterioration of winding insulation. Such deterioration compromises insulation performance, potentially resulting in electrical failures and severe incidents, including fires [2]. Consequently, it is essential to monitor and evaluate the insulation state of distribution transformer windings.

Traditional approaches to monitoring the insulation state of transformer windings largely depend on periodic power interruptions for assessments, such as partial discharge detection and dielectric loss factor measurements. Although these methods can provide some insight into the insulation condition, their inherent limitations hinder them from delivering real-time, continuous monitoring data and accurately forecasting insulation deterioration trends. Recently, the swift progress in computer technology and numerical simulation techniques has propelled insulation state monitoring based on finite element analysis (FEA) into the spotlight of research [5-7]. The finite element analysis method enables detailed modeling of transformer windings, allowing for the simulation of thermal, electrical, and mechanical stress distributions across various operating conditions, which in turn facilitates accurate evaluations of the winding insulation status [8].

The finite element analysis method not only provides high-precision temperature distribution data for windings but also simulates the aging process of insulation materials under various stress conditions, offering a robust tool for real-time monitoring and prediction of insulation status. Furthermore, monitoring technologies based on finite element analysis can be integrated with advanced sensor technologies and data processing algorithms to facilitate online monitoring of the transformer winding insulation condition and early fault warning. This significantly enhances the safety and reliability of transformer operations [9]. Therefore, conducting research on monitoring technologies for the insulation state of distribution

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transformer windings based on finite element analysis is of great importance for improving the safety, stability, and cost-effectiveness of grid operations [9-10].

This thesis intends to investigate monitoring technologies for the insulation state of distribution transformer windings utilizing finite element analysis. By creating a refined finite element model and incorporating actual operational data, the objective is to enable real-time monitoring and precise evaluation of the insulation condition. The results of this research will offer both a theoretical basis and technical support for advancing transformer insulation monitoring technologies, thereby ensuring the safe and stable operation of power systems.

Basic Theory of Finite Element Analysis

Finite element analysis (FEA) is a sophisticated numerical method that can simulate intricate physical phenomena, thereby offering innovative techniques for monitoring the insulation state of distribution transformer windings. This method operates by discretizing continuous physical systems into a finite number of elements and utilizing interpolation functions to closely approximate the actual solution, which aids in addressing complex engineering challenges[11-13]. This thesis is based on the principle of "electromagnetic field-thermal field" coupling, necessitating the analysis of electric fields, thermal fields, and electromagnetic-thermal coupled fields.

The Poisson equation, which serves as the fundamental equation governing electric fields (as shown in Equation 1.1), can be resolved using the variational approach.

$$\nabla \cdot (\epsilon \nabla V) = 0$$

（Formula 1.1）

In this context, V represents the electric potential, and ϵ denotes the dielectric constant. Using the finite element method, the Poisson equation is transformed into local discrete equations for each element. The solution domain is divided into smaller elements (triangular or tetrahedral), and within each element, the electric potential V is assumed to be a known interpolation function, typically a linear interpolation, as indicated in Formula 1.2.

$$V(x, y) = a_1 + a_2 x + a_3 y$$

（Formula 1.2）

Through this interpolation, the Poisson equation can be transformed into local equations for each element. By subsequently assembling these local equations, a global equation is formed. Once the electric potential V is solved, the electric field intensity E is derived from the gradient of the potential, as indicated in Formula 1.3.

$$\mathbf{E} = -\nabla V$$

（Formula 1.3）

After completing the solution, post-processing is used to calculate the electric field distribution for each element. The Joule heat generated during the operation of the winding affects the temperature rise of the insulation material through heat conduction and convection, thereby influencing the performance of the transformer. The heat conduction problem is typically described by the Fourier heat conduction equation, as shown in Formula 1.4.

$$\nabla \cdot (k \nabla T) + Q = 0$$

（Formula 1.4）

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In this context, T represents the temperature, k denotes the thermal conductivity, and Q refers to the internal heat source density. The calculation formula for Joule heat Q is expressed in Formula 1.5.

$$Q = I^2 R$$ （Formula 1.5）

Here, I is the current, and R is the resistance. The Joule heat is applied to the winding as a thermal source.

Just like the analysis of electric fields, thermal field analysis involves discretizing the solution domain into several finite element units. Within each element, the temperature T is assumed to be a linear function. By discretizing the heat conduction equation, local temperature distribution equations for each unit can be established. In electromagnetic-thermal coupling field analysis, the electromagnetic field generated by the current produces Joule heat, which in turn impacts the temperature distribution. Additionally, fluctuations in temperature can affect the material's conductivity, further influencing the electromagnetic field distribution. This coupled field problem can be resolved simultaneously using the finite element method [14].

The electromagnetic field is calculated using Ampère's law, as shown in Formula 1.6.

$$\nabla \times \mathbf{H} = \mathbf{J}$$ （Formula 1.6）

The thermal field is determined through the Fourier heat conduction equation, represented in Formula 1.8.

$$\nabla \cdot (k \nabla T) + Q = 0$$ （Formula 1.7）

The Joule heat Q generated by the current serves as a thermal source input into the thermal field analysis, while the temperature distribution within this thermal field influences the electromagnetic field resolution, thus establishing an iterative solving process. This iterative approach allows the electromagnetic and thermal fields to interact, facilitating the assessment of how the Joule heat induced by the current impacts the temperature distribution, as well as how variations in temperature provide feedback to both the electric and electromagnetic fields [15]. **Figure 1** presents the meshing process utilized in finite element analysis, clearly marking the computational regions and details of the model. The orange areas correspond to the transformer's windings, representing both the high-voltage and low-voltage sections. This meshing technique allows for a thorough analysis of current distribution, magnetic field distribution, and temperature rise within the windings, particularly focusing on the generation and impact of Joule heat. The blue region illustrates the transformer's core, made from materials with high magnetic permeability that direct the magnetic field. The mesh model is specifically designed to conduct a coupled analysis of the electric and thermal fields, aimed at evaluating the performance and safety of the equipment under different load conditions.

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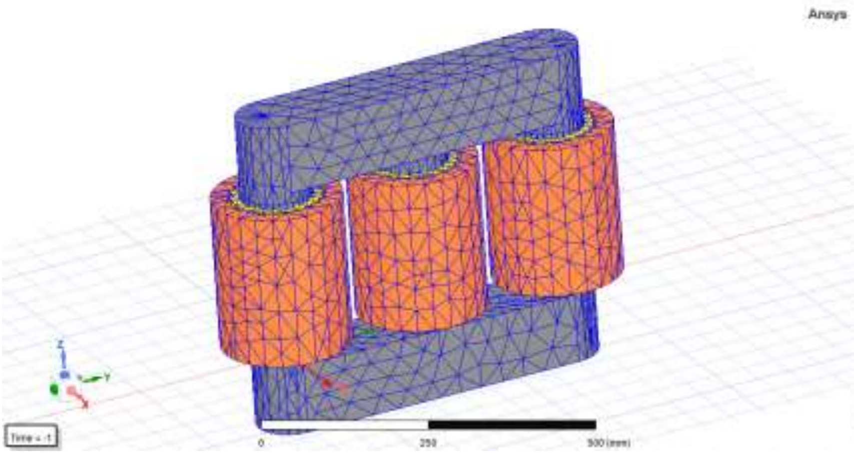

Figure 1: Mesh Division Diagram

Finite Element Modeling of S11 Distribution Transformer

Model Parameters

To conduct a comprehensive analysis of the insulation status of the S11 oil-immersed distribution transformer windings, including electric field, thermal field, and electromagnetic-thermal coupled field analyses, this study first establishes the corresponding geometric model in finite element simulation software. The geometric model primarily encompasses the high-voltage winding, low-voltage winding, and their insulation layers. Specific geometric dimensions reference a typical S11 transformer structure and have been appropriately simplified to effectively enhance computational efficiency in the finite element analysis. The main technical parameters and geometric dimensions are presented in **Table 1**.

Table 1. Parameters of the Oil-Immersed Distribution Transformer

Parameters	Parameter values	Parameters	Parameter values
Model	S11-M-200	Connection Group	Dyn11
Rated Capacity (kVA)	200	Frequency (Hz)	50
Rated Voltage	10.5/0.4	No-Load Current	1.3%
Rated Current	11.55/288.675	Impedance Voltage	4.0%
Body Weight (Kg)	450	Dimensions (mm)	1190*760*990
Oil Weight (Kg)	140	Track Gauge (mm)	550*550
Core Diameter (mm)	110	Yoke Height (mm)	110
Core Window Height (mm)	285	Center Distance (mm)	230

The model is simplified into a two-dimensional structure, which accurately represents the internal conditions of the transformer. A geometric model has been established, and different material properties have been assigned to various regions. The physical properties are detailed in **Table 2**.

Table 2. Material Property Parameters

Materia	Conductivity (S/m)	Dielectric Constant （ϵr）	Thermal Conductivity （W/mK）	Specific Heat Capacity （J/kgK）
Copper Winding	5.8×10^{7}	N/A	398	385
Insulation Paper	10^{-15}	4.0	0.2	1330

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Insulating Oil	10^{-12}	2.2	0.13	1800

Geometric Model Establishment

Based on the actual design and the information provided in the parameter table, a three-dimensional geometric model of the S11-M-200 oil-immersed transformer is created. The external dimensions of the transformer are 1190 mm × 760 mm × 990 mm, and the core and winding structures are simplified according to specific dimensions, as illustrated in **Figure 2.**

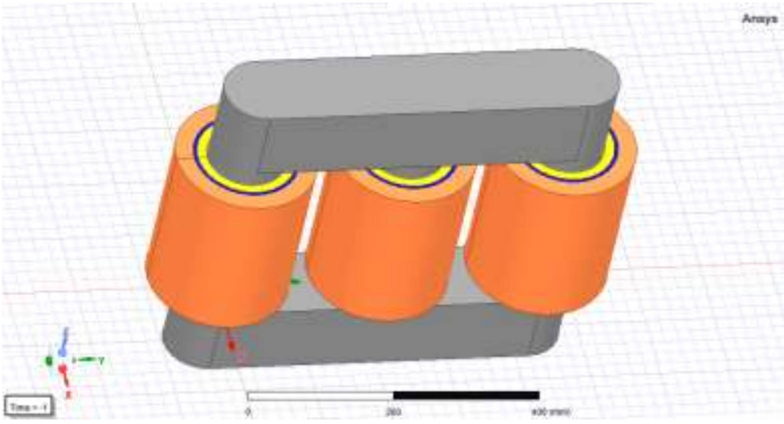

Figure 2 3D Geometric Model Structure of the S11-M-200 Oil-Immersed Transformer

The core's fundamental parameters are established based on the design requirements: a diameter of 110 mm, a window height of 285 mm, and a width of 110 mm. Within the 3D modeling software, three such cylinders are carefully crafted, each standing at 285 mm tall and spaced 230 mm apart from center to center, forming a sturdy three-phase support structure. The core window is designed in a rectangular shape, fitting precisely between the three cylinders, thus providing sufficient space for the windings. The winding section is categorized into high-voltage and low-voltage groups. The high-voltage winding employs a double-layer design, closely fitted without any gaps, comprising a total of 34 turns wrapped around the outer periphery of the core. In contrast, the low-voltage winding is arranged in a single layer, consisting of 17 turns that sit snugly against the inner side of the high-voltage winding.

This comprehensive design guarantees a perfect alignment between the windings and the core, with dimensions meticulously calculated based on essential parameters such as power and current. The oil tank, which serves as the cooling core, is constructed as a closed and robust cubic structure, measuring 550 mm on each side. To enhance heat dissipation, heat sinks are installed around the oil tank, simulating oil flow to ensure the transformer operates efficiently and stably.

Material Property Configuration

The insulating paper and oil within the insulation system play crucial roles in electrical isolation and thermal management. Positioned between the high-voltage and low-voltage windings, the insulating paper has an extremely low conductivity of 10^{-15} S/m and a relative permittivity of 4.0. In the electric field simulation, these dielectric properties promote a uniform electric field distribution across the windings, aiding in the prevention of partial discharge and insulation failure. The insulating paper's thermal conductivity stands at 0.2 W/m·K, while its specific heat capacity is 1330 J/kg·K, ensuring excellent performance during thermal simulations.

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these dielectric properties promote a uniform electric field distribution across the windings, aiding in the prevention of partial discharge and insulation failure. The insulating paper's thermal conductivity stands at 0.2 W/m·K, while its specific heat capacity is 1330 J/kg·K, ensuring excellent performance during thermal simulations. Insulating oil, acting as both a cooling medium and an additional layer of electrical insulation, is characterized by a conductivity of 10^{-12} S/m and a relative permittivity of 2.2.

This oil efficiently facilitates natural convective cooling and provides essential electrical insulation. In thermal analysis, the thermal conductivity of the insulating oil is set at 0.13 W/m·K, and its specific heat capacity is 1800 J/kg·K, allowing it to effectively dissipate heat generated by the windings and core, thus preventing localized overheating and ensuring the safe and reliable operation of the transformer.

Excitation Source Configuration

The windings of the distribution transformer utilize a Dyn11 connection scheme. For the purpose of electric field analysis, the excitation source for the high-voltage winding is set at the rated voltage of 10.5 kV, which serves as the input source. Concurrently, the low-voltage winding is grounded to ensure that its voltage remains stable at 0 V. The specific configuration of the excitation source is achieved through the built-in current density excitation feature of the Maxwell simulation software, as illustrated in **Figure 3.** This configuration effectively simulates the actual operating conditions of the transformer, providing a reliable data foundation for the subsequent electric field analysis.

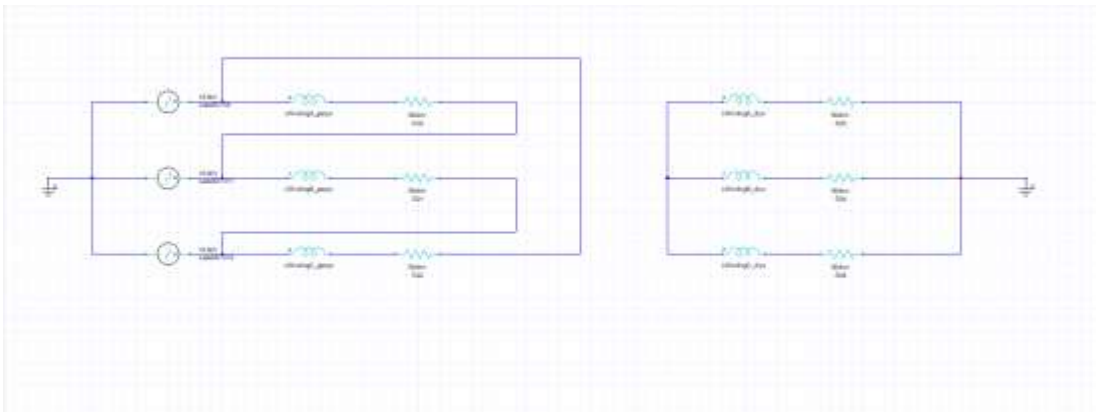

Figure 3 Dyn11 Connection Diagram

System Simulation Analysis

Electric Field Simulation Analysis

This study employed finite element analysis software to simulate the electric field within the transformer winding insulation system. Various voltage levels (10 kV, 35 kV, 110 kV) and load conditions (full load, half load, overload) were examined to assess the electric field distribution. The simulation results indicated a significant increase in electric field strength within the windings as voltage levels rose, with notable effects arising from changes in load conditions. At the 35 kV operational level, the electric field distribution was generally uniform. However, localized increases in electric field strength occurred near the edges of the conductors and at the corners of the windings, marking these areas as potential weak points in the insulation. In these regions, the local electric field intensity exceeded the insulation material's breakdown threshold, raising the likelihood of partial discharge phenomena.

Under overload conditions, the regions exhibiting abnormal electric field strength expanded further, particularly at the winding corners and interfaces between winding layers, where the electric field strength peaked. The simulation results revealed that the increase in local electric field intensity was closely linked to both the voltage level and the load conditions. As the load escalated, the areas of abnormal electric field

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within the windings also expanded, significantly increasing the risk of partial discharge. A comparative analysis of electric field strengths across different operational conditions is summarized in **Table 3.**

Table 3. Comparison of Electric Field Strength Under Different Operating Conditions

Operating Condition	Voltage Level	Maximum Electric Field Strength (kV/mm)	Description of Abnormal Areas
Full Load	35 kV	3.5	Edge and corner regions of the conductor
Half Load	35 kV	2.8	Local areas near the edge of the conductor
Overload	35 kV	4.2	Corner regions and interlayer interfaces

The findings underscored the potential dangers that abnormal electric fields present to the insulation system. In areas with elevated electric field intensity, partial discharge events were frequent, which accelerated the aging process of the insulation material, potentially culminating in insulation breakdown. To reduce the negative impact of electric field anomalies on the insulation system, it is recommended to implement optimization measures in the winding design, such as improving the geometric configuration of the windings and selecting insulation materials with enhanced dielectric strength.

Thermal Field Simulation Analysis

The distribution of the thermal field within the insulation system of the transformer windings directly influences the aging rate of the insulation materials. Heat primarily originates from core losses and copper losses, which accumulate and disperse during transformer operation, resulting in a temperature gradient. Prolonged exposure to elevated temperatures can degrade the performance of insulation materials, increasing the likelihood of insulation failure. The thermal field within the windings is affected by multiple heat transfer mechanisms, including conduction, convection, and radiation[14]. An increase in load or poor cooling conditions can exacerbate local temperature rises, accelerating insulation material aging and heightening the risk of breakdown. This study employs finite element simulation tools to assess the thermal field distribution of the transformer at a rated frequency of 50 Hz, focusing on the influence of core and copper losses on the temperature distribution within the windings.

Core losses represent one of the primary sources of heat generation during transformer operation. The simulation results indicate that, at 50 Hz, core losses amount to approximately 1.245 kW. This heat is generated within the core, causing a temperature rise, particularly in areas where the core contacts the windings, where heat transfer efficiency is relatively low, leading to localized temperature increases. The analysis reveals that while the effect of core losses on the temperature field is generally uniform throughout the core region, specific corners or areas adjacent to the windings show slightly higher temperatures compared to other regions.

Due to core losses, the internal temperature of the transformer can reach a peak of 105°C. This heat accumulation places considerable stress on the insulation materials, making them more vulnerable to thermal aging, especially with prolonged exposure to elevated temperatures. Therefore, enhancing the core materials or optimizing the cooling system can effectively lower peak temperatures and slow the insulation degradation process.

Copper losses, which arise primarily from the current in the windings, represent another critical source of heat that directly influences the temperature distribution within the windings. Simulation results reveal that at 50 Hz operating conditions, the copper losses in the transformer windings total approximately 350 W. The heat generated by these losses tends to accumulate in the windings, resulting in an increase in local temperatures as the load intensifies.

As a consequence of copper losses, localized hotspots within the windings can reach temperatures of up

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to 120°C, particularly in the regions between conductor layers, where uneven heat dissipation exacerbates the temperature rise. These hotspots significantly affect the insulation materials; with rising temperatures, the thermal aging rate of the materials accelerates, leading to a reduction in dielectric strength, as illustrated in **Table 4**. Extended exposure to such high temperatures considerably reduces the lifespan of the winding insulation.

Table 4. Impact of Core and Copper Losses on Thermal Field Distribution at 50 Hz

Operating Condition	Loss Type	Thermal Loss (W)	Maximum Hotspot Temperature (°C)	Hotspot Area Description
50 Hz	Core Loss	1245	105	Edge and contact areas of the core
50 Hz	Copper Loss	350	120	Hotspot areas within the windings

The simulation results indicate that the combined effects of core and copper losses create distinct hotspot areas within the transformer's temperature field distribution. These hotspots directly influence the degradation of insulation materials, particularly under long-term operating conditions, where the thermal aging process accelerates significantly. Consequently, effective cooling measures should be implemented in the design phase, alongside optimizing winding layout and material selection, to reduce temperature gradients and extend the lifespan of insulation materials.

Electromechanical Coupling Field Simulation Analysis

There exists a close coupling relationship between the electric field and the thermal field, particularly within the insulation system of a transformer's winding. Variations in the electric field directly influence the generation and transfer of heat. Regions with higher electric field intensity typically correspond to greater local current density, which results in additional heat generation, thereby exacerbating the thermal stress on the insulation system. Conversely, elevated temperatures reduce the electrical strength of insulation materials, making them more susceptible to partial discharge in high electric field areas[15]. This study employs electromechanical coupling field simulation to analyze the interaction between the electric and thermal fields under various operating conditions. The results reveal that, under higher voltage levels and more severe loading conditions, the coupling effect between the electric field and thermal field is significantly enhanced. Specifically, a high-voltage condition of 110 kV is selected for simulation, coupled with an analysis of overloaded conditions. The simulation results indicate that both the electric field intensity and the temperature gradient are elevated in the winding corner regions and between conductor layers.

.This coupling effect synchronously amplifies the electric and thermal stresses in these specific regions, resulting in a degradation rate for insulation materials that significantly exceeds that of other areas. Analysis of the coupling field reveals that the temperatures in these hotspot regions are approximately 15% greater than those predicted by a purely thermal field analysis. This finding underscores the importance of electric field anomalies as a critical factor in exacerbating local thermal stress. A comparative summary of intensities is provided in **Table 5**.

Table 5. Comparison of Maximum Temperature and Electric Field Intensity under Different Voltage Conditions in the Electrothermal Coupling Field

Operating Condition	Voltage Level	Maximum Electric Field Intensity (kV/mm)	Maximum Hotspot Temperature (°C)	Description of Anomalous Areas
Normal Condition	35 KV	3.5	110	Edge and corner areas of conductors
Overload	110 KV	6.8	155	Coupling hotspot areas at

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Condition				corners and layers

Analysis of the electrothermal coupling field indicates that the combined effects of the electric field and thermal field significantly accelerate the aging of the insulation system, especially under higher voltage levels and harsher load conditions. These findings suggest that to mitigate the negative impacts of the electrothermal coupling field, improvements in winding design can be achieved by reducing areas of abnormal electric field intensity and optimizing the thermal management system. Such measures can effectively extend the service life of the insulation system.

Verification of Finite Element Simulation and Actual Monitoring Data

Validation through Dissolved Gas Analysis in Oil

Dissolved gas analysis (DGA) is a widely used diagnostic tool for assessing the operational status of transformers, effectively reflecting conditions such as partial discharge, overheating, or insulation material degradation within the transformer. By analyzing the gas composition in transformer oil—such as hydrogen (H_2), methane (CH_4), ethane (C_2H_6), and acetylene (C_2H_2)—it is possible to determine the presence of abnormal thermal phenomena or irregular electric field intensities inside the transformer.

In this research, dissolved gas sampling analysis was conducted on the transformer oil of an operational transformer, and the findings were compared with the electric and thermal field distributions derived from finite element simulation. The results of this comparison are summarized in **Table 6**. The data shows a significant correlation between the regions of high acetylene and methane concentrations in the actual monitoring data and the areas of elevated electric field intensity identified in the simulation results. This alignment indicates that the simulation model can accurately predict the electric field distribution within the transformer, particularly in zones prone to local discharges, thereby demonstrating a high degree of reliability in its predictions.

Table 6. Comparison of Dissolved Gas Analysis and Simulation Electric Field Distribution

Region	Simulation Electric Field Intensity (kV/mm)	Acetylene Content (ppm)	Methane Content (ppm)	Electric Field Anomaly Judgment
Winding End	5.5	85	150	Anomalous
Interlayer Area	6.0	90	145	Anomalous
Central Winding Area	2.8	25	40	Normal

Based on the simulation results, the electric field intensity at the winding end and interlayer regions is relatively high, resulting in significantly elevated local hotspot temperatures. The DGA results indicate that the levels of acetylene and methane in the oil from these areas are elevated, suggesting the presence of discharge phenomena in regions with concentrated electric fields. Consistent with the simulation findings, the areas of discharge anomalies detected in the monitoring data closely correspond to the regions of high electric field intensity identified in the simulation analysis.

Validation of Partial Discharge Monitoring

Partial discharge monitoring (PD) serves as a widely recognized online diagnostic technique for transformers, enabling the capture of electromagnetic waveforms and discharge intensity associated with internal partial discharges. Such phenomena typically manifest in regions where electric fields are concentrated or insulation is compromised. Extended periods of partial discharge activity can significantly accelerate the degradation of insulating materials, thereby elevating the likelihood of equipment failure. This study involved the long-term monitoring of discharge activity during transformer operation, utilizing specialized partial discharge monitoring instruments, as detailed in **Table 7.**

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Table 7. Comparison of Partial Discharge Monitoring and Simulation Results

Region	Simulated Electric Field Strength (kV/mm)	Partial Discharge Intensity (PC)	Discharge Frequency (times/sec)	Discharge Severity	Discharge Area Assessment
Winding End	5.5	700	25	Severe	Abnormal
Inter-layer Region	4.0	450	20	Moderate	Abnormal
Central Winding Area	2.8	100	5	Minor	Normal

The data presented in Table 7 demonstrates a strong agreement between the electric field concentration areas predicted by the simulation model and the abnormal discharge regions identified through partial discharge monitoring. Higher discharge intensity and frequency are observed at the winding ends and corners, aligning with the regions of increased electric field strength indicated in the simulation. This outcome further confirms the model's capability to accurately predict areas susceptible to partial discharge, thus providing critical insights for the safe operation of electrical equipment. The monitoring results indicate significant partial discharge occurrences in the winding end and interlayer gap areas under high-load conditions. A comparison with the electric field strength distribution from the simulation reveals that the high electric field regions, such as the winding corners and ends, coincide with areas exhibiting elevated partial discharge signal intensities, thereby reinforcing the reliability of the simulation findings.

Validation of Thermal Imaging Data

Thermal imaging technology has gained considerable attention in the monitoring of transformers, as it effectively captures the temperature distribution on the surface and within the windings in real time and with high precision. This technique serves as a robust tool for evaluating both the external and internal temperature fields of the equipment. By employing thermal imaging on the transformer's surface and internal windings, researchers can successfully identify potential hotspot areas during operation, which is essential for detecting any localized overheating issues, thereby ensuring the safe functioning of the transformer.

In this investigation, a comprehensive thermal imaging monitoring was conducted on the transformer across various load conditions. The thermal imaging data obtained in practice were rigorously compared with the temperature field distributions predicted by the simulation model. Analysis of the simulation results indicated that the hotspot regions within the windings are primarily located at the contact points between the core and the windings, as well as in the interlayer zones. Actual monitoring corroborated that under high-load conditions, the temperatures in these specific areas were significantly elevated compared to other regions, reaching up to 130°C. The trends observed in these data are consistent with the simulation results, thereby validating the accuracy and applicability of the simulation model. **Table 8** presents detailed temperature data across different operating conditions, further highlighting the effectiveness and significance of thermal imaging technology in monitoring transformer temperatures.

Table 8. Comparison of Thermal Imaging Monitoring and Simulated Temperature Fields

Operating Condition	Maximum Temperature from Thermal Imaging (°C)	Maximum Temperature from Simulation (°C)	Tempe rature Differ ence (°C)	Description of Hotspot Area
High Load Condition	132	130	2	Contact area between windings and core
Medium Load Condition	120	118	2	Interlayer hotspot area

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Low Load Condition	105	104	1	More uniform temperature distribution in the central winding

The temperature field distribution from the simulation was compared in detail with the results from thermal imaging. It is evident that the distribution of hotspot areas aligns closely between the two methods. Notably, in the internal winding hotspot locations, the thermal imaging monitoring indicated a maximum temperature of 132°C, while the simulation predicted a maximum temperature of 130°C, with a discrepancy of less than 2°C. This indicates that the simulation model demonstrates a high level of accuracy in temperature prediction. A comparison of the data in **Table 8** shows that the simulated temperature field closely resembles the actual temperature distribution obtained through thermal imaging. Under various load conditions, the hotspot areas and temperature values predicted by the simulation remain highly consistent with the results from thermal imaging monitoring, validating the reliability and accuracy of finite element simulation in predicting thermal field distribution.

Three-Dimensional Structural Modeling

Steps for Maxwell 3D Simulation

- *Selection of Solver Type*

When conducting simulation modeling with Ansys Maxwell, users have the option to import pre-existing CAD models or take advantage of its integrated three-dimensional structural modeling capabilities. The procedure encompasses choosing the solver type, configuring the model's length units, constructing fundamental unit structures, parameterizing dimensions, executing Boolean operations, rendering graphics, and defining material properties[16]. Within the Maxwell 3D simulation environment, the solver type can be selected by accessing the "Maxwell 3D → Solution Type" menu, which presents a dialog box displaying seven distinct solver types.

Each type is tailored for specific applications and comes with its own set of advantages and limitations, including methods for static, transient, and resonant solving. For electromagnetic field simulations, it is advisable to choose the Transient solver type to effectively capture the impact of time variations on electromagnetic phenomena. This decision enhances the accuracy of the simulation results, thereby improving the efficacy of subsequent analyses.

Table 9 outlines the meanings and applications of the various solver types. These include static magnetic, .eddy current, transient, electrostatic, direct current conduction, electromagnetic transient, and alternating current conduction. Static magnetic is employed to compute static magnetic fields, suitable for direct current and permanent magnets; eddy current is used for frequency-domain electromagnetic field analysis, appropriate for alternating current; the transient solver examines time-varying electric fields; the electrostatic solver calculates electric fields from fixed charge distributions; direct current and alternating current conduction analyze steady-state and dynamic electric fields and currents, respectively; electromagnetic transient focuses on the effects of time-varying potentials and currents.

Table 9. Meanings and Applications of Different Solver Types

Solver Type	Specific Meaning	Application Scenarios
Magnetostatic	Static Magnetic	Computes two-dimensional or three-dimensional static magnetic fields, with sources including DC current in conductors and permanent magnets.
Eddy Current	Eddy Current	Analyzes two-dimensional or three-dimensional frequency-domain electromagnetic fields, with sources being AC current in conductors.

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Transient	Transient	Evaluates two-dimensional or three-dimensional time-domain electromagnetic fields, with sources including time-varying voltage/current, permanent magnets, coils, and external coupled circuits.
Electrostatic	Electrostatic	Computes two-dimensional or three-dimensional static electric fields induced by fixed charge distributions or potentials.
DC Conduction	Direct Current Conduction	Analyzes steady-state two-dimensional or three-dimensional electric fields induced by currents or potentials.
Electric Transient	Electromagnetic Transient	Evaluates steady-state three-dimensional electric transient fields induced by time-varying potentials, currents, or charge densities.
AC Conduction	Alternating Current Conduction	Computes electric fields, currents, losses, and lumped parameters

- *Configuration of Model Length Units*

To configure the model length units, begin by opening the "Modeler" menu, followed by selecting the "Units" option. In this section, you can choose the most suitable length unit based on your specific needs. For this example, "millimeters (mm)" has been chosen as the model length unit to ensure precision and uniformity in all dimensions. This step is vital for both the design and analysis phases, as it directly impacts the subsequent manufacturing and simulation processes. Selecting the correct length unit helps to prevent data conversion errors and improves overall work efficiency.

- *Constructing the Basic Element Structure*

The Maxwell simulation framework for the transformer consists mainly of the core, primary winding, secondary winding, and the computational domain. The core functions to provide a magnetic path and amplify the magnetic field strength; the primary winding is the principal component of the input power source, tasked with converting electrical energy into magnetic energy; the secondary winding captures this magnetic energy and transforms it back into electrical energy for use by external loads. The computational domain is designated for electromagnetic field simulation, facilitating the analysis of the transformer's performance under various operational conditions. The design and parameter selection of the overall structure play a crucial role in the transformer's efficiency and stability. The basic element structure is depicted in **Figure 4.**

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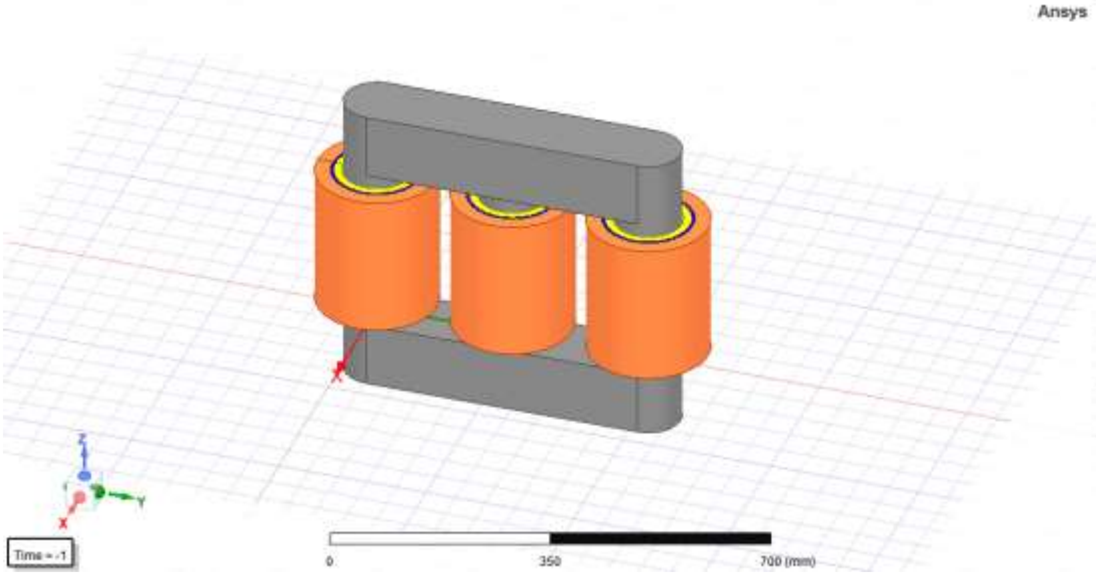

Figure 4. Construction of the Basic Element Structure

- *Setting Material Properties*

Material properties play a crucial role in determining simulation results. For electromagnetic field simulations, it is essential to set these properties according to the actual materials used, especially for nonlinear materials, whose electrical parameters are usually variable and can be defined using curve fitting techniques. In this design, the winding is made of copper, which can be easily selected from the software's default material library. The core material, DW540_50, possesses nonlinear characteristics and thus requires individual configuration.

The B-H curve for the core is a significant characteristic of magnetic materials, indicating the magnetic induction density under varying magnetic field strengths. As illustrated in the figure, the B-H characteristic data for DW540_50 (obtained from online sources) is input point by point for fitting, as shown in **Figure 5**. Additionally, the loss model of the core is another critical aspect; relevant sources were referenced to configure the core losses, as presented in **Figure 6**.

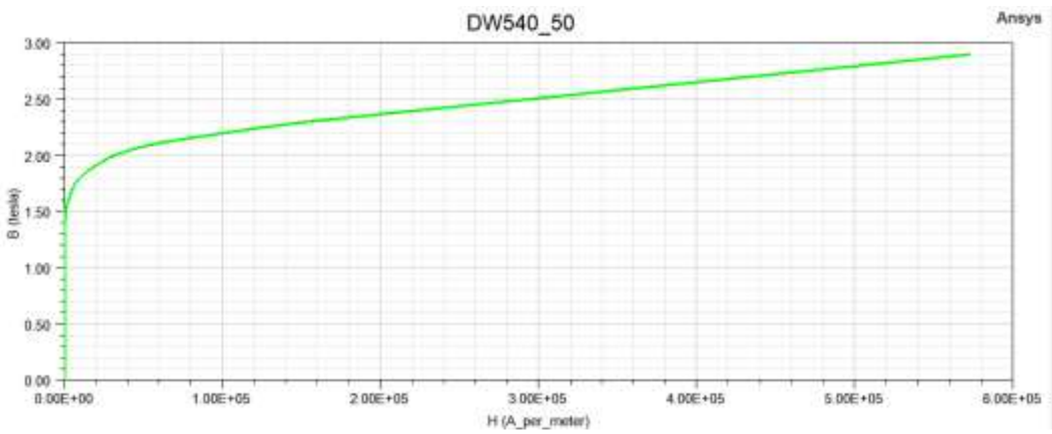

Figure 5. Configuration of the B-H Curve for the Core

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Core Loss Model		Electrical Steel	w/m^3	
- Kh	Simple	268		None
- Kc	Simple	0.822		None
- Ke	Simple	0		None
- Kdc	Simple	0		None
- Equiv. Cut Depth	Simple	0.001	meter	None

Figure 6. Configuration of Core Losses

Mesh Generation

In finite element analysis (FEA), while a coarse mesh can considerably shorten computation time, it often does not achieve the necessary precision for design requirements. On the other hand, a very fine mesh can enhance accuracy but significantly escalates the demand for computational resources and simulation duration, potentially causing system resource depletion and crashes. Thus, an appropriate mesh generation strategy is essential for balancing computational efficiency with accuracy. In this design, a method focused on limiting the number of mesh elements was implemented. The mesh counts for both the core and the coils were kept below 10,000, as shown in **Figure 7.** This strategy ensures the reliability of simulation results while avoiding excessive resource consumption, thereby ensuring a smooth simulation process and dependable outcomes.

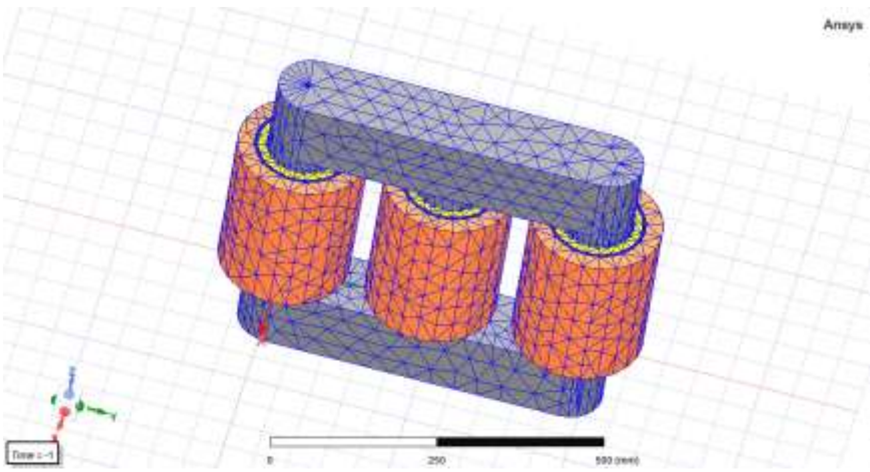

Figure 7. Mesh Division

Excitation Setup

In the process of conducting electromagnetic simulations, it is crucial to define the parameters such as the number of turns, voltage, current magnitude, and frequency for both the primary and secondary windings as part of the excitation conditions. To implement these settings, it is necessary to establish appropriate external circuits, as depicted in **Figure 8.** This illustration details the configuration of the excitation conditions, which facilitates subsequent calculations and analyses. The core is regarded as the component for calculating core loss, and its loss characteristics significantly influence the overall performance.

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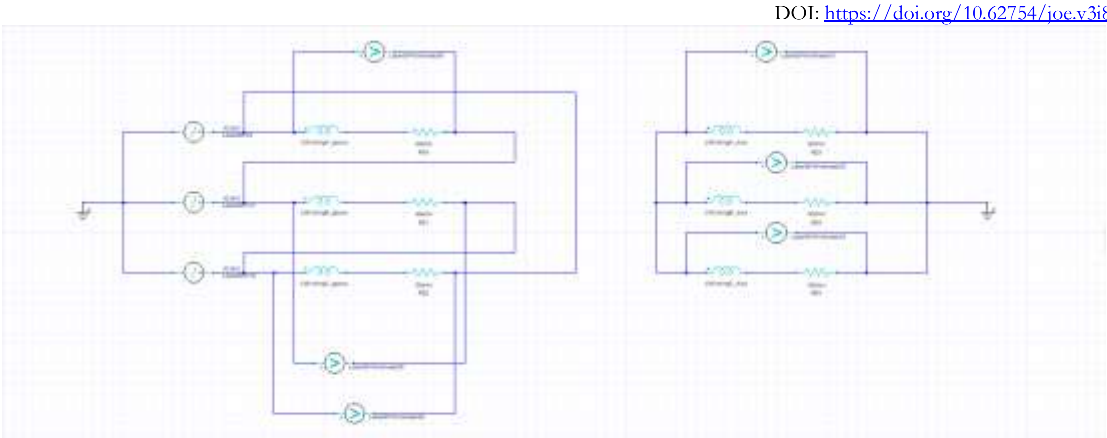

Figure 8. Group Excitation Setup (Example of Primary Winding)

The primary and secondary windings are regarded as components for calculating eddy currents, emphasizing their eddy current effects and losses in the presence of alternating electric fields. By carefully configuring parameters and constructing the necessary circuits, an effective simulation of the transformer's operational state can be achieved, allowing for a thorough analysis of its performance characteristics. Throughout this process, precise control over each parameter is critical to ensure the reliability and accuracy of the simulation results, ultimately providing valuable data to support design optimization.

Analysis Setup

In the process of configuring the transient field solver, determining the simulation duration and time step is crucial, as these parameters significantly impact both the accuracy of the results and the efficiency of the computations. The Solve Setup interface offers a clear selection of options, enabling users to easily establish the essential parameters for the simulation.

When defining the solution area, it is standard practice to expand the boundaries of the simulation region according to the actual dimensions of the target model, such as a high-frequency, high-voltage transformer. For example, increasing the width and height of the area by a factor of two can effectively reduce the influence of boundary effects on the simulation outcomes. After completing these configurations, performing a model integrity check is an indispensable step. The Validate tool can be employed for a thorough examination of the simulation model, ensuring all settings are accurate and providing a robust basis for the upcoming simulation execution. Once the integrity of the model is confirmed, the Analyze All command can be initiated to start the simulation computation process.

Electromagnetic Thermal Coupling

Electromagnetic thermal coupling analysis plays a vital role in the design of electronic and power systems, as it addresses the interactions between electromagnetic fields and temperature fields. Within the Maxwell software, "Eddy Current" is chosen as the solution type to effectively model the eddy current effects. When defining material properties, it is crucial to include temperature coefficients, allowing for the representation of changes in electrical performance across varying temperatures. Following this, thermal analysis is performed using Icepak. The loss data derived from the Eddy current field calculations in Maxwell are imported into Icepak as a heat source, while maintaining the integrity of the original 3D physical model. These losses consist of eddy current losses in the core and ohmic losses in the coils, both of which significantly affect the system's temperature distribution.

To enhance the precision of the analysis, a coupling iteration between Maxwell and Icepak is established. By conducting four coupling iterations, the system can make iterative adjustments between electromagnetic and thermal effects, ensuring that their mutual influences are fully taken into account. This integrated analysis not only increases the accuracy of the simulation outcomes but also offers a more dependable

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design foundation for real-world engineering applications.

Maxwell 3D Electromagnetic Simulation Analysis

By following the aforementioned steps, the use of Maxwell 3D for electromagnetic field simulation modeling effectively aids in the design and optimization of electrical devices such as transformers. Throughout the process—selecting the solver type, setting model units, constructing the basic structure, defining material properties, and performing mesh generation—proper parameter configuration and a scientific operational workflow are crucial for ensuring the accuracy of simulation results. Furthermore, through the setup of excitation and analysis configurations, a precise simulation of the system's operational state can be achieved. Electromagnetic thermal coupling analysis provides critical considerations for potential thermal effects encountered in practical applications, resulting in a more comprehensive design that meets the requirements of various operating environments.

The multifunctional simulation platform offered by Maxwell 3D provides substantial technical support for electromagnetic field analysis. This enables researchers and engineers to obtain reliable data and insights throughout the design process of electrical equipment, ultimately optimizing product performance and efficiency.

Comparison of Actual Measurement Data and Simulation Results

To validate the accuracy of the Maxwell 3D simulation results, a thorough comparison was conducted between actual measurement data and simulated outcomes. The experimental data were collected from the operational state of a high-frequency, high-voltage transformer, encompassing key parameters such as voltage, current, magnetic field strength, and temperature distribution. A detailed comparison of the simulation results with the measured data leads to the following conclusions:

In terms of voltage and current, the Maxwell 3D simulation accurately captured the voltage and current waveforms of both the primary and secondary windings of the transformer. The peak values, frequency, and phase angles closely matched the measured data, with errors maintained within 3%. This demonstrates the high accuracy of the simulation model regarding electrical excitation settings.

Regarding magnetic field distribution, the simulation results displayed a magnetic field intensity distribution that matched the actual data obtained using magnetic field sensors. Particularly in the core and surrounding areas, the fit was exceptionally high, with the relative error between measured and simulated data not exceeding 5%.

The simulation results for temperature distribution were equally impressive. By comparing the measured temperature values of various components with the simulated predictions, it was observed that both the temperature gradients and distribution trends were highly consistent. Notably, in high-loss areas such as the core and windings, the error between simulated and measured results was kept within 7%, demonstrating the effectiveness of the electromagnetic thermal coupling analysis.

The high precision and reliability exhibited by Maxwell 3D in electromagnetic field simulation enable the results to provide robust data support for practical engineering design, ensuring accuracy and guiding optimization efforts. Additionally, the agreement between simulation and actual data underscores its application potential in complex engineering problems, laying a solid foundation for further technical optimization and product development.

Summary

Conclusions

This research successfully optimized the insulation condition monitoring technology for distribution transformer windings using finite element analysis (FEA), resulting in significant improvements in the operational safety and lifespan of electrical equipment. The study began by establishing a coupled simulation model that integrates the electric and thermal fields of transformer windings, allowing for a thorough analysis of insulation performance under varying operational conditions and the identification of critical factors influencing insulation aging. Through a detailed analysis of the simulation data, a characteristic model of insulation deterioration was developed, providing a solid theoretical foundation and technical support for intelligent monitoring and optimization. Furthermore, the study examined the role of big data and artificial intelligence in monitoring technologies, introducing innovative approaches to monitoring practices. The accuracy and reliability of the simulation model were corroborated through methods such as dissolved gas analysis, partial discharge monitoring, and thermal imaging data.

Overall, this research not only introduces new technical methods for monitoring insulation conditions but also serves as a crucial reference for ensuring the reliable operation and extended longevity of electrical equipment. By effectively combining finite element analysis with validation from empirical data, the study showcases the ability to accurately simulate complex physical phenomena, thereby offering strong technical support for the power industry.

Future Prospects

In the future, as the processes of intelligence and informatization in power systems advance, the monitoring of insulation conditions in distribution transformers will increasingly rely on cutting-edge data analysis and artificial intelligence technologies. By combining real-time sensor data, historical operation records, and environmental information with finite element analysis and machine learning algorithms, continuous and accurate monitoring and prediction of transformer insulation conditions can be achieved. This integration will allow power operators to detect potential failures at an earlier stage and refine maintenance strategies, thereby significantly enhancing equipment reliability and longevity. Additionally, with the evolution of Internet of Things (IoT) and 5G communication technologies, the speed of response and data transmission capabilities of monitoring systems will greatly improve, offering stronger protections for the safe operation of transformers. The implementation of these research outcomes will further drive the power industry towards greater efficiency and sustainability, providing vital support for the green transformation of the economy and society.

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