

Article

Temperature Field Simulation of Oil-Immersed Transformers Based on Electro–Thermal–Mechanical Multiphysics Coupling

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Abstract

To address the issues of thermal non-uniformity and insulation aging of converter transformers operating under long-term high electric field and high-temperature conditions in ultra-high-voltage direct current (UHVDC) transmission systems, this paper investigates the temperature field distribution characteristics of converter transformers based on electro–thermal–mechanical multiphysics coupling. By establishing a full-scale multiphysics simulation model of a ± 800 kV converter transformer, the interactions among the electric field, temperature field, and mechanical stress field are comprehensively considered. The temperature gradient distribution and hotspot formation mechanisms within the valve-side winding and the lead-out structure are revealed. The results show that the internal temperature distribution of the converter transformer is non-uniform, resulting in a nonlinear distribution of material parameters in oil-paper insulation, which significantly affects the insulation performance. The research findings provide a theoretical basis and engineering reference for the structural optimization and thermal stability improvement of the main insulation system of converter transformers.

Keywords: oil-immersed transformer; temperature field; electro–thermal–mechanical multiphysics coupling; simulation analysis; insulation performance

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1. Introduction

Compared to AC transmission, DC transmission offers unique advantages in terms of transmission distance and capacity [1–3]. As a critical component of DC transmission systems, converter transformers have attracted widespread attention in recent years. Unlike conventional transformers, converter transformers are subjected to composite AC/DC voltages during operation, and their winding currents contain a significant amount of harmonic components [4]. Their main insulation systems must not only withstand strong electric fields but are also simultaneously affected by various factors such as temperature gradients, mechanical stress, and vibration [5,6]. Under long-term operation, the coupled effects of these factors can easily lead to insulation aging, partial

discharge, and degradation of dielectric properties, becoming key factors limiting equipment lifespan and operational reliability.

In recent years, the rapid development of ultra-high-voltage DC transmission projects has placed higher demands on the electrical, thermal, and mechanical performance of converter transformer insulation systems. To ensure the high reliability of these critical assets, the power industry has increasingly relied on advanced intelligent power operation and maintenance technologies. Various cutting-edge methodologies, including transformer inspection robots, advanced target detection algorithms, and industrial defect detection frameworks, have been widely deployed to capture early-stage symptoms of equipment anomalies [7–9]. However, internal insulation degradation inside oil-immersed core components often begins under extreme multi-physical stress, which remains invisible to external visual sensors. Even when utilizing thermal infrared or visual cameras mounted on inspection robots, severe ambient conditions or low-light industrial environments frequently distort the captured data, necessitating advanced low-light image enhancement techniques to restore critical visual details [10,11]. Despite the rapid evolution of these external intelligent diagnostics, a critical knowledge bottleneck persists: external phenomenological detection and target recognition algorithms fundamentally lack a deep coupling with the internal, high-fidelity physical evolution mechanisms. Without a clear understanding of how interior physical fields interact and trigger material degradation, it is extremely difficult for inspection robots or diagnostics frameworks to accurately predict deep-seated insulation failures or establish proactive defense strategies.

Traditional design and analysis methods are primarily based on single-physical-field assumptions, making it difficult to accurately describe the coupling effects of electric and temperature fields under complex operating conditions, nor can they reveal the impact of thermal stress on the structural stability of the insulation system. In multi-infeed DC systems, the electrical coupling and interactions among multiple DC lines further exacerbate the complexity of converter transformer operating conditions [12]. Research indicates that under AC voltage, the dielectric constant of materials remains virtually unchanged with respect to temperature, electric field strength, and other factors, resulting in a linear electric field distribution; under DC voltage, the resistivity of materials varies with factors such as temperature and electric field strength [13,14], leading to a redistribution of the electric field and the formation of local hot spots. This thermo-electro-mechanical interaction is one of the primary causes of insulation performance degradation in converter transformers [15]. Therefore, there is an urgent need to establish simulation models capable of reflecting multiphysics interactions to enable accurate assessment of the temperature field and insulation performance of converter transformers.

To address the aforementioned issues, this study develops an engineering-scale electro–thermal–mechanical coupled model for a ± 800 kV oil-immersed converter transformer. The critical bottleneck addressed in this work lies in the severe mismatch of local electrical parameters caused by the non-uniform temperature field, especially within the highly complex valve-side winding end region. The novelty of this work does not lie in proposing a new finite-element algorithm, but in integrating the loss distribution, oil-flow heat transfer, temperature-field mapping, and oil–paper insulation parameter variation into a unified analysis procedure for the main insulation system and valve-side winding end region of a UHVDC converter transformer [16,17]. Compared with existing studies that mainly focus on conventional transformer winding temperature rise or single thermal-fluid analysis [18,19], this work emphasizes the thermal behavior of the valve-side end insulation under converter-transformer operating conditions and further discusses how the non-uniform temperature field affects the electrical parameters and insulation performance of oil–paper insulation [20]. By bridging the gap between internal

multiphysics interactions and material parameter evolution, this research not only optimizes the structural insulation design but also provides a foundational physical-mechanism paradigm to fuel future digital twins and internal fault-targeted intelligent detection algorithms [21].

2. Magnetic, Thermal, and Mechanical Fields in a Full-Scale Converter Transformer

To investigate the thermal distribution characteristics and insulation property variations in converter transformers under complex operating conditions, a two-dimensional model based on actual geometric dimensions is established in this paper, taking an oil-immersed converter transformer with the model ZZDFPZ-415 000/500-800 as an example; the designation ZZDFPZ-415000/500-800 is a Chinese engineering model code for a UHVDC converter transformer. In this designation, ZZDFPZ denotes the converter-transformer product series; 415000 denotes the rated capacity, i.e., 415,000 kVA/415 MVA; 500 denotes the grid-side AC voltage level; and 800 denotes the corresponding ± 800 kV DC transmission voltage level. The main technical parameters are listed in Table 1. The model is solved using the finite element method (FEM), enabling the coupled calculation of the electric field, temperature field, and mechanical stress field, so as to reveal the influence mechanism of multiphysics interactions on temperature distribution and insulation performance. Such an electro – thermal – mechanical numerical framework accounts for the simultaneous parameter mapping and stress generation across distinct physical domains [22].

Table 1. Main Parameters of Converter Transformers.

Main Items	Parameter Values
Rated capacity	415 MVA/415 MVA (grid-side winding/valve-side winding)
Rated voltage	$(530/\sqrt{3})/(165/\sqrt{3})$ kV
Maximum phase-to-phase AC voltage of valve-side winding	178 kV
Maximum DC voltage per valve bridge	204 kV
Cooling method	ODAF
Vector group	Ii0
Temperature rise limits	Top-oil: 45 K; winding hotspot: 61 K
DC transmission voltage level	± 800 kV

2.1. Overall Model Structure and Computational Domain Division

The main winding components of the converter transformer include: core 1, located at the center to form the main magnetic circuit; tap winding 2, arranged outside the core for voltage regulation; grid-side winding 3, connected to the AC grid; valve-side winding 4, positioned outermost and connected to the converter valve; oil-impregnated pressboard 5, serving as insulation and support between windings and at ends; transformer oil 6, flowing from the bottom inlet to the top outlet through oil ducts for insulation and cooling; and electrostatic ring 7, installed at winding ends to homogenize the electric field and improve end insulation performance, as shown in Figure 1.

To ensure computational accuracy while maintaining solution efficiency, a locally refined meshing strategy is adopted for different regions. In particular, the insulation structures and winding end regions are treated as key refinement areas to accurately capture local electric field and temperature gradient variations.

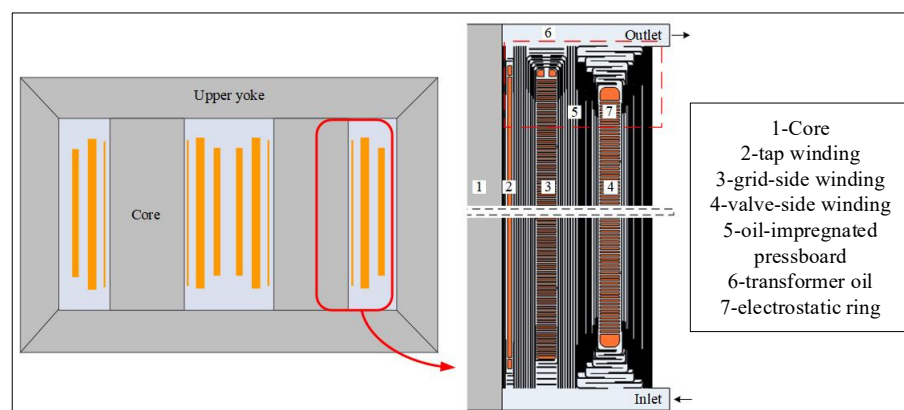


Figure 1. Calculation Model of ± 800 kV Converter Transformer.

2.2. Establishment of the Electromagnetic Field Simulation Model for Spatial Effects of Converter Transformers

The main insulation of a converter transformer refers to the insulation between the windings and all other components except the windings themselves. It mainly includes the insulation between windings and grounded parts such as the core, clamping structures, and oil tank, the insulation between different windings, as well as the insulation between leads and grounded parts and among leads of different windings. End insulation also falls within the category of main insulation.

Under AC voltage, the electric field distribution in oil–paper composite insulation depends on the dielectric constant ϵ and exhibits a capacitive field distribution; under DC voltage, it depends on the resistivity ρ of the materials and exhibits a resistive field distribution. Specifically, under an AC field, the electric field strength in the oil medium is higher than that in the solid medium; therefore, the AC electric field in a transformer is mainly concentrated in the oil gaps. However, under a DC field, the electric field strength in the solid medium is higher than that in the oil medium. The resistivity of transformer oil is on the order of $10^{13} \Omega \cdot m$, while that of insulating pressboard is on the order of $10^{15} \Omega \cdot m$. This indicates that the DC electric field strength in the pressboard is approximately 100 times that in the transformer oil. Therefore, in converter transformers, the DC electric field is mainly concentrated in solid insulation materials. Consequently, although both converter transformers and AC transformers employ oil–paper insulation structures, the insulating pressboard in converter transformers plays an equally important role as the insulating oil.

As the main insulation of a transformer, the insulation between windings and between windings and ground generally adopts an oil–barrier insulation structure composed of insulating pressboard and transformer oil. End insulation refers to the insulation between the winding ends and the upper and lower yokes, as well as between adjacent winding ends. It is an important part of the main insulation system of converter transformers. The electric field in this region is highly non-uniform, making it prone to surface discharge. The end insulation adopts an oil–paper barrier structure, and the curvature of the insulating angle rings is designed to follow the equipotential lines of the electric field as closely as possible.

The upper-end structure of the converter transformer winding is shown in Figure 2. From left to right: tap winding 1, composed of multiple longitudinal conductor layers; grid-side winding 2, surrounded by multi-layer bent winding structures; valve-side winding 3, positioned innermost; insulating pressboard 4, filling the gaps between windings for inter-layer insulation and support; electrostatic ring 5, installed at the top of the valve-side winding to homogenize the end-region electric field; and formed angle ring

6, a multi-layer bent angular insulation structure surrounding the grid-side winding end to enhance end insulation performance. All gap media are transformer oil.

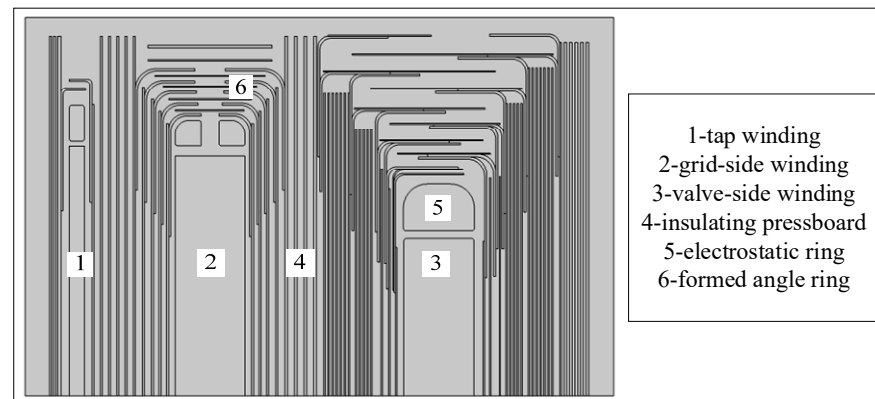


Figure 2. Converter Transformer End Insulation Model.

The high-voltage electrostatic ring 4 is placed at the end of the converter transformer winding. It is an open metallic ring with a certain thickness, typically formed by wrapping metal foil or braided metal strips around a framework made of insulating material, or directly manufactured with a metallic core and externally wrapped with insulating paper. The electrostatic ring not only improves the electric field distribution at the winding end but also forms additional capacitance between the ring and the end winding discs, thereby improving the initial potential distribution of the winding under impulse voltage.

The angle ring 6 is an arc-shaped insulating component with inward or outward flanges. Its functions are twofold: on the one hand, it increases the insulation distance at the winding end to prevent surface discharge; on the other hand, it divides the oil gaps at the winding end, splitting a long oil gap in a highly non-uniform electric field into several smaller gaps, so that each gap maintains a relatively uniform insulation margin, thereby improving insulation utilization.

2.3. Establishment of the Temperature Field Simulation Model for Spatial Effects of Converter Transformers

2.3.1. Load Capacity Calculation of Converter Transformers

During normal operation of a converter transformer, the magnetic field generates losses in the core, windings, and structural components. These losses are converted into heat, which is dissipated through heat conduction and convection in the oil, in the form of both forced and natural oil circulation, resulting in a non-uniform temperature distribution inside the transformer. In the practical operation of UHVDC transmission systems, the converter valve is a nonlinear component and serves as a major source of harmonics. The generated harmonics lead to increased harmonic currents in the converter transformer, intensified vibration, and increased core losses. In this study, the loss analysis does not consider the losses of structural components such as clamping parts, pressing plates, magnetic shields, and copper shields; only the losses generated in the core and windings by the magnetic field are taken into account.

The no-load losses of a converter transformer mainly consist of hysteresis loss, eddy current loss, and additional loss in the core. Among them, hysteresis loss and eddy current loss are closely related to the material properties, thickness, and grain orientation of the silicon steel sheets, while the additional loss mainly depends on the core design and manufacturing process. The converter transformer studied adopts high-quality cold-rolled grain-oriented silicon steel sheets, combined with advanced design and manufacturing processes, ensuring that under rated tap and rated voltage conditions

without DC bias current, the no-load loss of the LY-connected converter transformer meets the specified value of 153 kW, while that of the LD-connected converter transformer meets the specified value of 149 kW. In addition, for converter transformers, the effect of DC bias on no-load losses must also be considered. According to the requirements, the long-term DC bias current (referred to the grid side) is 12 A. Calculations show that the no-load loss increases by approximately 27 kW for the LY-connected transformer and by approximately 23 kW for the LD-connected transformer when DC bias is taken into account.

Common methods for calculating core loss can be divided into two categories: one based on hysteresis mathematical models and the other based on loss separation models. In engineering practice, the loss separation model is more widely used, in which the core loss of laminated silicon steel is divided into hysteresis loss, eddy current loss, and excess loss. Taking the commonly used electromagnetic analysis software MagNet as an example, the core loss under harmonic conditions can be expressed as:

$$P = K_h f^a B^b + K_e (sfB)^2, \quad (1)$$

where B is a function of magnetic flux density, and s is the lamination thickness ratio of the silicon steel sheets. The coefficients K_h , K_e , a , and b are obtained by fitting the input loss curve data. The first term on the right-hand side of the equation represents the sum of hysteresis loss and excess loss, while the second term represents eddy current loss.

For core loss under distorted magnetic flux containing high-order harmonics, the eddy current loss can be derived as:

$$K_e (fB)^2 = \frac{\pi \sigma d^2}{6} f^2 \sum_h^{NH} h^2 B_h^2, \quad (2)$$

where d is the thickness of a single silicon steel sheet, NH is the highest harmonic order, and B_h is the amplitude of the h -th harmonic, which can be obtained using the harmonic balance finite element method.

Load losses mainly consist of ohmic loss and eddy current loss. Under harmonic conditions, the ohmic loss of the winding is calculated as:

$$P_R = \sum_{h=1}^{NH} k_h^2 \cdot P_{WR}, \quad (3)$$

The eddy current loss of the winding under harmonic conditions is calculated as:

$$P_E = P_{WEI} \times P_{WE} = P_{WEI} \times \sum_{h=1}^{NH} (k_h^2 \cdot h^2), \quad (4)$$

where P_E is the winding eddy current loss at the fundamental frequency, and K_h is the ratio of the frequency of the h -th harmonic current to that of the fundamental current frequency.

The oil pump of the converter transformer drives the cooling oil to circulate, removing the heat generated in the core, windings, and structural components through convective heat transfer. The heat dissipation process of the core, windings, structural components, and oil satisfies the three conservation laws: conservation of mass, momentum, and energy [23]. The corresponding governing equations can be expressed by the following general equation:

$$\frac{\partial(\rho u \varphi)}{\partial z} + \frac{\partial(\rho v \varphi)}{\partial r} = \frac{\partial}{\partial z} \left(\lambda \frac{\partial \varphi}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial z} \left(\lambda r \frac{\partial \varphi}{\partial r} \right) + S, \quad (5)$$

where φ represents a general variable (here, temperature); λ and S are the diffusion coefficient and the generalized source term, respectively; ρ is the density of the insulating oil; and v and u are the velocity components in the x and y directions, respectively.

2.3.2. Loss Analysis of Converter Transformers

In this study, a magnetic field and loss calculation model of the converter transformer is first established. In the calculation of core losses, the influence of up to the 7th harmonic is considered. The winding ohmic losses are obtained by constructing a DC transmission simulation model in PSCAD/EMTDC. The present simulation focuses on the temperature distribution under the rated operating condition, and the corresponding load losses were used as the thermal input of the model. After spectrum analysis, harmonics up to the 30th order are taken into account according to their amplitude variations. The calculated losses are listed in Table 2.

Table 2. Core and Winding Losses.

Load Condition/(kW)	Main Tap	Minimum Tap
No-load loss	150	150
DC resistive loss	740	816
Winding eddy current loss	77	75
Harmonic loss	60	53

The density, viscosity, and specific heat capacity of mineral transformer oil are affected by temperature; however, since its coefficient of volumetric expansion is small, it can still be considered an incompressible fluid. The parameters of the core, windings, and paper are less affected by temperature and are therefore set as constants. The relevant physical properties [24] are shown in Table 3, where T denotes the absolute temperature in Kelvin.

Table 3. Material Physical Properties Parameters.

Material	Parameter	Value
mineral transformer oil	Density/($\text{kg}\cdot\text{m}^{-3}$)	$p_p = 1\,098.72 - 0.712T$
	Thermal conductivity/($\text{W}\cdot(\text{m}\cdot\text{K})^{-1}$)	$\lambda = 0.1509 - 7.01 \times 10^{-5}T$
	Specific heat capacity/($\text{J}\cdot(\text{kg}\cdot\text{K})^{-1}$)	$c_p = 1\,744.73 + 4.2T$
	Dynamic viscosity/($\text{Pa}\cdot\text{s}$)	$\mu = 0.0846 - 4 \times 10^{-4}T + 5 \times 10^{-7}T^2$
	Relative permittivity	2.2
Core	Electrical conductivity/($\text{S}\cdot\text{m}^{-1}$)	1.0×10^{-13}
	Density/($\text{kg}\cdot\text{m}^{-3}$)	7650
	Thermal conductivity/($\text{W}\cdot(\text{m}\cdot\text{K})^{-1}$)	45
Winding	Specific heat capacity/($\text{J}\cdot(\text{kg}\cdot\text{K})^{-1}$)	460
	Density/($\text{kg}\cdot\text{m}^{-3}$)	8900
	Thermal conductivity/($\text{W}\cdot(\text{m}\cdot\text{K})^{-1}$)	338
Insulating paper	Specific heat capacity/($\text{J}\cdot(\text{kg}\cdot\text{K})^{-1}$)	390
	Density/($\text{kg}\cdot\text{m}^{-3}$)	1200
	Thermal conductivity/($\text{W}\cdot(\text{m}\cdot\text{K})^{-1}$)	0.25
	Specific heat capacity/($\text{J}\cdot(\text{kg}\cdot\text{K})^{-1}$)	2000
	Relative permittivity	4
	Electrical conductivity/($\text{S}\cdot\text{m}^{-1}$)	1.0×10^{-15}

The outlet pressure of the converter transformer is set to zero, and the ambient temperature is assumed to be room temperature (298 K). Based on the heat sources in Table 2 and the physical properties in Table 3, the following parameters are set in the finite

element simulation software COMSOL6.3: the inlet oil velocity of the winding is 0.2 m/s, the outlet pressure is zero, and the ambient temperature is 298 K.

The inlet oil velocity, material thermal properties, and thermal boundary conditions are important factors affecting the absolute temperature values and local temperature gradients. In the present model, these parameters were set according to the available engineering data and material-property expressions. The inlet oil velocity mainly determines the convective heat-transfer capacity in the oil ducts, while the thermal conductivity of oil–paper insulation affects the heat-transfer path from the winding to the surrounding oil. The ambient temperature and outlet-pressure boundary conditions influence the overall thermal-fluid solution. Since a systematic parametric sensitivity analysis was not conducted in this study, the present results are mainly interpreted as the temperature-distribution trend and hotspot tendency under the adopted parameter settings.

3. Simulation Results and Analysis

Considering that the end region of the valve-side winding has a complex structure, larger temperature gradients, and stronger nonlinear coupling characteristics, this study selects the end region of the valve-side winding as the research object. The electrical conductivity of materials is obtained from experimental measurements. Based on the temperature distribution derived from thermo-fluid coupling, the node mapping method is employed to transfer data, and the temperature field simulation results are interpolated and mapped onto the corresponding mesh elements for electric field calculation. The mapped two-dimensional computational model is shown in Figure 3.

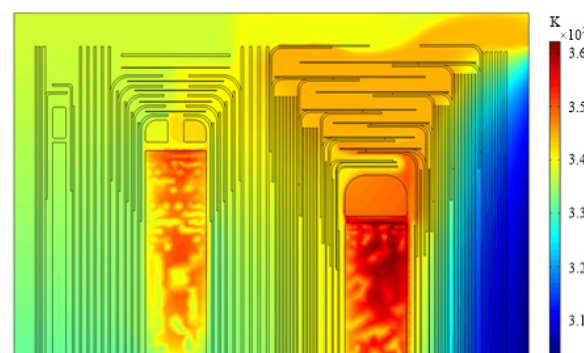


Figure 3. Temperature Distribution at the Winding Ends.

Figure 4 presents the temperature distribution contour of the entire transformer. It can be observed that the temperature at the winding ends is relatively high. The highest temperature occurs near the winding end, because there are no additional heat-generating winding discs above the top disc, and the wider oil channel above facilitates heat dissipation. The temperature rise in the insulating oil in this region reaches 48.4 K. Based on computational fluid dynamics analysis of flow and heat transfer in the transformer windings, the average temperature of the grid-side winding is 330.81 K, while that of the valve-side winding is 337.05 K, and the hotspot temperature reaches 362.22 K. The average temperature rise in the windings is less than 50 K, and the maximum hotspot temperature rise can be controlled below 68 K, all of which satisfy the relevant standard requirements.

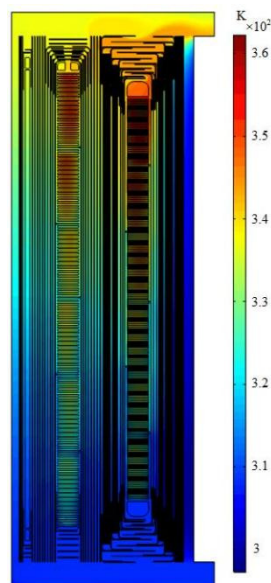


Figure 4. Temperature Distribution Contour Map of the Converter Transformer.

The axial temperature distribution curve of the valve-side winding is shown in Figure 5. The results indicate that the winding temperature increases nonlinearly along the vertical direction and exhibits periodic peaks and valleys corresponding to the spacing of oil ducts. This is because the transverse oil flow velocity at the inlet and outlet of each section is relatively high, removing more heat, which causes the temperature within each section to first decrease and then increase. The average temperature rise in the windings is less than 50 K, and the maximum hotspot temperature rise can be controlled below 68 K, all of which satisfy the relevant standard requirements.

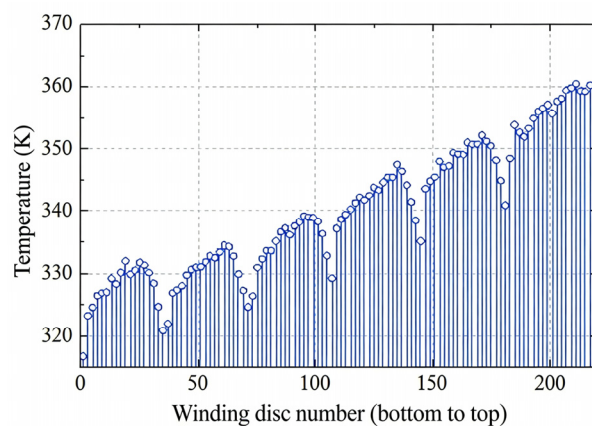


Figure 5. Axial Temperature Distribution Curve of Valve-Side Winding.

As temperature increases, the viscosity of transformer oil decreases and the activation energy of conductive ions increases, leading to an exponential increase in the electrical conductivity of transformer oil. Similarly, in oil-impregnated pressboard, the energy of impurity ions increases with temperature, enabling them to more easily escape the constraints of cellulose molecules, thereby increasing the number of charge carriers and resulting in an exponential increase in conductivity. It can be seen that the nonlinear relationship between temperature and the conductivity of oil–paper insulation leads to significantly different calculation results, thereby affecting the design of insulation and temperature rise in converter transformers.

From the above analysis, it can be concluded that the internal temperature distribution of the converter transformer is non-uniform, with significant temperature gradients. The presence of temperature gradients leads to a nonlinear distribution of material parameters in oil–paper insulation. Moreover, temperature has a much greater influence on the conductivity of insulating pressboard than on that of transformer oil, which further aggravates the mismatch of electrical parameters in oil–paper insulation and may lead to insulation failures such as surface flashover, thereby significantly affecting insulation performance [25].

The present study did not conduct a systematic parametric sensitivity analysis; therefore, a strict quantitative ranking of the parameters affecting hotspot formation was not obtained. Based on the simulated temperature distribution and heat-transfer mechanism, hotspot formation is mainly governed by the loss distribution in the winding end region and the local oil-flow heat-transfer condition. The axial temperature fluctuation shown in Figure 5 is closely related to the oil-duct arrangement, indicating that the oil-flow condition has a direct influence on local heat removal. In addition, the thermal conductivity of oil–paper insulation, the temperature-dependent oil properties, and the ambient thermal boundary condition may affect the absolute temperature level and local temperature gradient. These factors are therefore regarded as important uncertainty sources in the present model.

In practical application, the geometric parameters, rated operating condition, loss data, cooling-oil velocity, material properties, and boundary conditions of a specific transformer are first introduced into the finite-element model. The coupled temperature-field calculation is then used to identify the hotspot region, evaluate the temperature gradient in the main insulation system, and assess whether the temperature rise satisfies the design and standard requirements. Based on the calculated hotspot location and temperature distribution, the transformer designer can further adjust the oil-duct arrangement, local insulation structure, cooling strategy, or thermal margin of the valve-side winding and end-insulation region.

4. Conclusions

This work established an engineering-scale electro–thermal–mechanical coupled model for the main insulation system and valve-side winding end region of a ± 800 kV oil-immersed converter transformer. The main scientific contribution is not the development of a new FEM algorithm, but the establishment of an insulation-oriented analysis procedure linking converter-transformer loss distribution, oil-flow heat transfer, temperature gradients, and oil–paper insulation parameter variation. The results identify the valve-side winding end and lead-out region as the main hotspot regions and further indicate that the non-uniform temperature field may aggravate the mismatch of electrical parameters in oil–paper insulation, thereby affecting the insulation reliability of the main insulation system.

The research results provide theoretical support for the integrated electro–thermal–mechanical design of the main insulation system of converter transformers and can be used to guide insulation structure optimization and thermal management strategies for UHVDC converter transformers. In the future, the combination of online monitoring and digital twin technologies can be further explored to achieve real-time prediction and active regulation of temperature field variations. In summary, the proposed electro–thermal–mechanical multiphysics coupling modeling and optimization method can effectively reveal the formation mechanism of the temperature field in converter transformers and its relationship with insulation performance, providing a reliable theoretical and engineering basis for improving operational reliability and extending service life.

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