HEAT DISSIPATION PERFORMANCE ANALYSIS AND COOLING MODULE OPTIMIZATION OF OIL-IMMERSED TRANSFORMER BASED ON MULTI-PHYSICAL FIELD SIMULATION

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The long-term operation of the oil-immersed transformer will cause the internal temperature to rise rapidly, which may lead to accidents such as transformer burning, which has a certain impact on the safe and reliable operation of the power grid. In this paper, the model of oil-immersed transformer is established by finite element simulation software, and the three-dimensional circuit magnetic field simulation model is established according to the structural parameters of the transformer, and the core loss and winding loss of the transformer are calculated accurately. The calculated loss is loaded into the simulation model of the flow temperature field, and the distribution characteristics of the temperature field and flow field of the transformer core and winding are obtained accurately by analyzing the heat transfer mode of the transformer and calculating the convection heat transfer coefficient formula in the heat convection theory. According to the structure of the transformer winding, the main variable parameters of the winding that affect the transformer temperature rise are selected. Through the center composite design method and range analysis, the winding geometry parameters which minimize the hot spot temperature of the transformer are obtained. In order to further reduce the temperature rise of the transformer, the principle of enhanced heat dissipation is used, and the cooling module is attached to the radiator of the transformer model, and the shape, installation position, installation method and number of the cooling module are changed respectively. Through heat flow coupling calculation, the optimal structure and installation mode of heat dissipation performance are obtained: symmetrical rectangular cooling module is installed at the upper end of the heat sink, which can effectively reduce the hot spot temperature of the transformer. The results show that the hot spot temperature of the oil-immersed transformer can be reduced from 78.1 ℃ to 60.7 ℃, and the hot spot temperature can be reduced by 22.3%. The above research provides a new idea and reference for oil immersed transformer to reduce temperature rise and improve heat dissipation performance.

Key words: *Oil-immersed transformer; Temperature distribution; Central composite design method; Cooling module*

1. Introduction

Oil-immersed transformer, as the key equipment in the power system, plays the role of transmitting electric energy. Transformers have wide distribution range and large quantity, and their reliable operation is directly related to the quality of power supply. In recent years, with the gradual increase of electricity demand, the safe operation of oil-immersed transformers has been put to a severe test. With the increase of transformer voltage level and capacity, the hot spot temperature may exceed the allowable value, resulting in transformer burnout, spontaneous combustion and other accidents, which seriously threaten the stable operation of the power grid. According to GB/T6451-2015, for every 6℃ increase in transformer temperature, life loss will double and service life will be reduced by half. Therefore, in order to ensure the safe and stable operation of the power grid, it is very important to analyze the heat dissipation performance of the oil-immersed transformer and optimize the cooling module on the basis of accurately calculating the temperature distribution characteristics of the transformer.

In recent years, scholars at home and abroad have carried out a lot of research on the temperature distribution calculation and heat dissipation performance optimization of transformers. (1) In terms of temperature field calculation, literature [1] established a two-dimensional axisymmetric leakage magnetic field model of an oil-immersed transformer and calculated the eddy current loss density distribution in the transformer as a heat source to obtain the transformer temperature distribution. In literature [2], the governing equations of heat transfer and fluid flow were solved by combining the finite volume and finite difference methods to calculate and obtain the temperature distribution of the transformer. In literature [3], the governing equations describing the physical behavior of fluid flow and heat transfer are solved using finite volume method. In literature [5], the effects of thermal buoyancy and Prandtl number on the flow characteristics of different cylinders and mixed convection heat transfer in Newtonian fluids are studied by two-dimensional numerical data. In literature [7], the effects of thermal buoyancy on the heat transfer characteristics of different heated/cooled cylinders in vertical channels are obtained through two-dimensional numerical simulation. In literature [8], the influence of natural convection control parameters on fluid motion and heat transfer rate in the heated cylinder and the influence of thermal buoyancy strength on fluid motion and temperature in the circular wall of the cold surface is studied by numerical simulation. (2) In terms of heat dissipation performance optimization: Literature [10] reduces hot spot temperature by installing a fan at the bottom of the transformer for forced air cooling. Literature [11] reduces the hot spot temperature of transformer by replacing the type of transformer oil as a whole. Literature [12] analyzed the influence of winding hot spot temperature and overload capacity under different cooling methods. In literature [13], the radiator of the transformer was installed in horizontal and vertical ways, and the hot spot temperature of the transformer under different conditions was obtained and analyzed. Literature [15] combines computational fluid dynamics and genetic algorithm to reduce the hot spot temperature of transformer by changing the size of transformer coil and cooling pipe. Literature [17] analyzed the different heat dissipation effects of transformer manifold by changing its tilt Angle. Literature [18] studied the equivalent treatment method of transformer radiation-convection combined heat dissipation. Literature [19] proposes to install high-overload distribution transformers instead of ordinary distribution transformers to cope with overload. Literature [20] proposed a heat dissipation method by adding a heat dissipation water pipe between the transformer core and the low voltage winding. The above literature and existing studies all involve the calculation of transformer temperature field, analysis of transformer overheating phenomenon, and methods and design schemes to improve transformer heat dissipation performance. However, most of them calculate and analyze transformer temperature field by establishing two-dimensional simplified models. The obtained temperature field and flow field distribution are not comprehensive, and the optimization of heat dissipation structure is relatively simple at present. Only unilateral optimization, high cost, a single method and difficult to operate, did not take into account the overall optimization of the transformer from multiple aspects.

Based on the previous research work and multi-physical field simulation analysis, this paper intends to build an oil-immersed transformer simulation model through COMSOL finite element software, calculate the transformer magnetic field distribution, and obtain the transformer core and winding loss distribution based on the magnetic field distribution, and further use the loss as a heat source. It is loaded into the established simulation model of transformer flow field-temperature field, and the simulation results of transformer temperature field and flow field are obtained through calculation, based on which the temperature distribution of transformer is analyzed. According to the heat dissipation characteristics of the transformer, the main variable parameters affecting the temperature rise are determined, and the optimization calculation is carried out according to the influence of winding structure parameters, the shape of the heat dissipation module, the installation conditions and the installation number, and finally the comprehensive conditions for the optimal heat dissipation of the transformer are obtained. The results show that this optimization method can effectively reduce the hot spot temperature of the transformer, greatly improve the heat dissipation performance of the transformer, and can be well applied in engineering and practice, so as to ensure the safe and stable operation of the power system.

2. The Basic Structure and Equivalent Model of Transformer

2.1. The basic structure and parameters of transformer

In this paper, the three-phase oil-immersed transformer is taken as the research object, and its main electrical parameters are shown in Table 1. Among them, the winding is divided into low-voltage winding and high-voltage winding, the iron core is composed of cold-rolled silicon steel sheet stacked, the oil tank is filled with transformer oil, which plays the role of heat transfer, and the cooling system is composed of chip heat sink to realize the natural circulation cooling of oil.

Table 1 Main Electrical Parameters of Transformers

Parameter	Value (Model)
Phase number	3
Linkage group	Dyn11
Rated frequency	50Hz
Rated voltage	220kV
High voltage winding radius	253mm
Low voltage winding radius	184mm

Winding height	640mm
Distance between winding and tank	217mm
Core height	1280mm

2.2. Transformer Equivalent Model

Based on the actual structure parameters of the transformer, the 3D simulation model of the oil-immersed transformer is constructed by COMSOL finite element software. Considering the influence of the internal structure of the oil-immersed transformer on the calculation, in order to facilitate the calculation, the following assumptions and simplifications are made when establishing the model: 1) Ignore the transformer clamp, pull plate and other structures; 2) The winding is simplified into a cylinder form, and the height is regarded as the same; 3) The central connection of the winding is symmetrical. The three-dimensional equivalent model and internal structure of the transformer are shown in Fig.1 (a) and Fig.1 (b) respectively. The winding coils are divided into three phases: A, B and C.

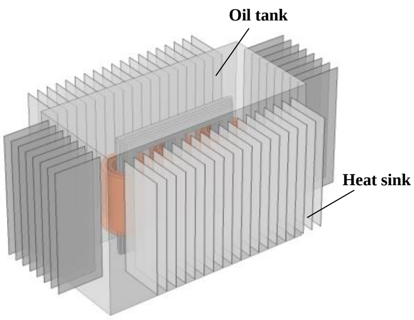

Figure 1 (a). Three Dimensional Equivalent Model of Transformer

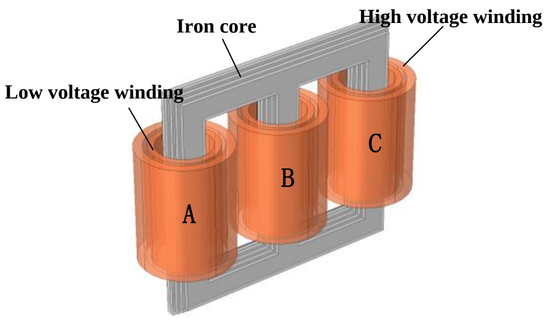

Figure 1 (b). Internal Structure of Transformer

3. Multi-physical field simulation of transformer

3.1. Governing Equation and Calculation Method

3.1.1 Magnetic field governing equation

Maxwell's equations are the basis of electromagnetism, consisting of four equations, describing the electric field, magnetic field and charge density, current density relationship, it reflects the essential correlation between electromagnetic phenomena, is the basis of transformer magnetic field calculation.

$$\begin{cases} \nabla \cdot \vec{B} = 0 \\ \nabla \cdot \vec{D} = \vec{\rho} \\ \nabla \cdot \vec{E} = -\dfrac{\partial \vec{B}}{\partial t} \\ \nabla \cdot \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t} \end{cases} \tag{1}$$

In the formula: $\vec{B}$ is the magnetic flux density; $\vec{D}$ is the electric displacement vector; $\vec{\rho}$ is the charge density; $\vec{E}$ is the electric field strength; $\vec{H}$ is the magnetic field strength; $\vec{J}$ is the current density.

Maxwell's equations themselves do not contain the properties of the medium, so when the electromagnetic field propagates in the medium, the characteristics of the medium need to be taken into account, which must be realized by the constitutive equation of the medium.

$$\begin{cases} \vec{B} = \mu \vec{H} \\ \vec{D} = \varepsilon \vec{E} \\ \vec{J} = \sigma \vec{E} \end{cases} \tag{2}$$

In the formula: μ is the permeability; ε is the dielectric constant; σ is the conductivity.

3.1.2 Flow field governing equation

During the heat transfer process, the oil-immersed transformer relies on the natural convection process of the oil flow to transfer heat.

$$\begin{cases} \nabla \cdot u = 0 \\ \left(\rho_f u \cdot \nabla\right) u + \nabla p + \eta \nabla \times \omega = f \\ \omega - \nabla \times u = 0 \\ u\big|_{\Gamma_1} = u_0 \end{cases} \tag{3}$$

In the formula: ρ_f is the fluid density; p is the internal pressure of the fluid; η is the hydrodynamic viscosity coefficient; f is the external force density vector; u is the oil flow velocity vector; u_0 is the boundary value of oil flow velocity; ω is vorticity, that is, the degree of rotation of the fluid; $u\big|_{\Gamma_1}$ is the boundary component of the oil flow velocity vector.

3.1.3 Temperature field governing equation

The governing equation of temperature field of oil-immersed transformer is:

$$\begin{cases} \nabla \cdot \left(\rho_f c_p u T\right) - \nabla \cdot \lambda \nabla T = S_T \\ T\big|_{\Gamma_1} = T_0 \\ -\lambda \left.\dfrac{\partial T}{\partial n}\right|_{\Gamma_{2,3}} = h\left(T - T_a\right) + q_s \end{cases} \tag{4}$$

In the formula: n is the normal direction; h is the thermal conductivity; T_a is the ambient temperature; q_s is the heat flux; $-\lambda \left.\dfrac{\partial T}{\partial n}\right|_{\Gamma_{2,3}}$ stands for normal heat flux; c_p is the specific heat capacity at constant pressure; λ is the thermal conductivity; S_T is the heat source, which is the loss per unit volume inside the transformer.

3.2. Loss analysis

3.2.1 Analysis of transformer core loss

Transformer core loss refers to the energy loss caused by the action of alternating magnetic field in the transformer main magnetic circuit, which is mainly generated by the winding excitation current.

According to the above calculation method, the transformer core volume loss density distribution is shown in Fig.2:

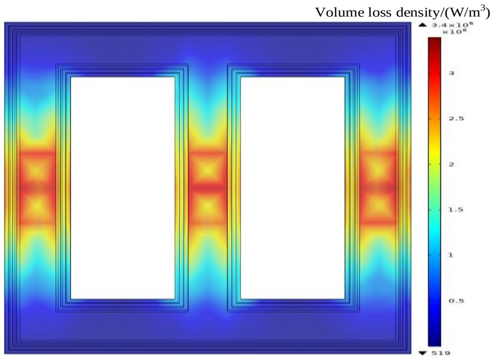

Figure 2. Loss Density Distribution of Core

It can be seen from the schematic diagram of the volume loss density of the iron core that the loss density distribution is symmetrical, the minimum value is located at the four top angles and edges of the iron core, the maximum value is distributed in the middle area of the iron core column, and the maximum loss density is 3.4×10^{6}W/m^{3}.

3.2.2 Analysis of transformer core loss

Transformer winding loss refers to the heat loss caused by the winding resistance in the transformer and the eddy current loss caused by the transformer core. These losses are unavoidable energy conversion losses during transformer operation and have a direct impact on transformer efficiency and performance. After calculation, the volume loss density distribution of transformer winding is shown in Fig.3:

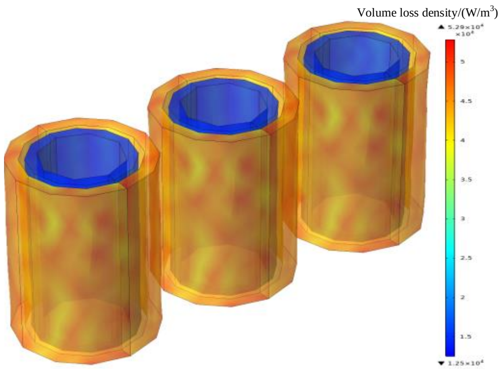

Figure 3. Loss Density Distribution of Wingdings

As can be seen from the schematic diagram of winding volume loss density distribution, the loss density of high-voltage winding is greater than that of low-voltage winding as a whole, and its distribution is asymmetrical, with the maximum loss density being 5.29×10^{4}W/m^{3}.

3.3. Material property

The material Settings for the main parts of the transformer are shown in Table 2. The iron core and winding are set according to the characteristic parameters of soft iron and copper respectively, and the fluid part in the tank is transformer oil, because the physical property parameters of transformer oil will vary with the change of temperature, so it is set as a temperature function in degrees Celsius.

Table 2   Material Property Settings

Material	Features	Value
Iron core (soft iron)	thermal conductivity /($W \cdot m^{-1} \cdot K^{-1}$)	51.9
	specific heat volume /($J \cdot kg^{-1} \cdot K^{-1}$)	485
	density /($kg.m^{-3}$)	7550
Winding (copper)	thermal conductivity /($W \cdot m^{-1} \cdot K^{-1}$)	401
	specific heat volume /($J \cdot kg^{-1} \cdot K^{-1}$)	385
	density /($kg.m^{-3}$)	8933
Transformer oil	thermal conductivity /($W \cdot m^{-1} \cdot K^{-1}$)	$0.134\text{-}8.05\times10^{-5}T$
	specific heat volume /($J \cdot kg^{-1} \cdot K^{-1}$)	$-13408.15+123.04T\text{-}0.33T^2$
	density /($kg.m^{-3}$)	$1055.05\text{-}0.58T\text{-}6.4\times10^{-5}T^2$

3.4. Boundary conditions and mesh generation

In the transformer temperature field simulation calculation, the ambient temperature is set to 20℃, considering that the transformer tank shell and heat sink are heat transfer with the surrounding air by convection, so it is very important to accurately calculate the convection heat transfer coefficient of each surface. According to the calculation method of convective heat transfer coefficient in literature [14], the convective heat transfer coefficient of each wall on the surface of the transformer tank can be obtained, as shown in Table 3 below.

Table 3 Convective Heat Transfer Coefficient on the Surface of Transformer

Convective heat transfer coefficient	Box top	Box bottom	Box side	Heat sink
$W/(m^2 \cdot k)$	47	47	55	55

3.5. Temperature field simulation

Taking the loss density of the transformer's iron core and winding as the heat source, the overall temperature distribution of the transformer can be obtained through simulation calculation, as shown in Fig.4. Among them, the hot spot temperature of the transformer is 116.0℃, which is located at the connection between the wall of the transformer oil tank and the heat sink. On this basis, the temperature distribution of transformer core and winding is extracted and analyzed by the whole temperature distribution of transformer[4].

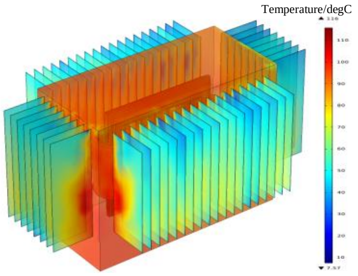

Figure 4 (a). Temperature distribution of integral transformer

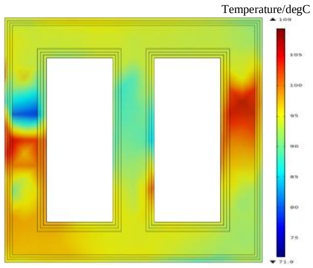

Figure 4 (b). Temperature distribution of iron core

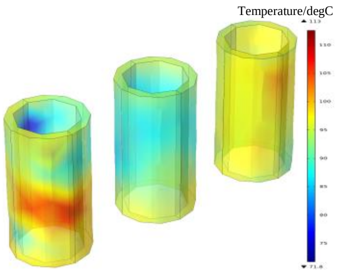

Figure 4 (c). Temperature distribution of low voltage winding

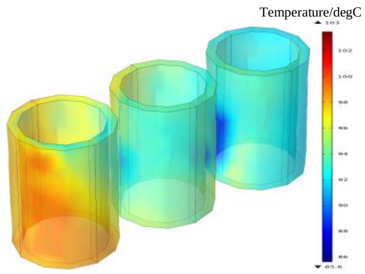

Figure 4 (d). Temperature distribution of high voltage winding

As can be seen from Fig.4, when the temperature reaches a stable state, for the transformer as a whole, the surface temperature of the oil tank is significantly higher than that of the heat sink, and the transformer oil transfers heat to the outside world through the heat sink. The temperature in the contact area between the heat sink and the oil tank wall is higher than that in other parts of the heat sink, and the surface temperature of the heat sink presents an uneven distribution; for the core, the highest temperature is 109.0℃, located in the middle and upper part of phase C; for the winding, the overall temperature of the low-voltage winding is higher than that of the high-voltage winding, and the highest temperature of the low-voltage winding and the high-voltage winding is distributed in the middle region of the A-phase coil, and the overall temperature of the A-phase coil is higher than that of the other two phases. Because the heat generated by the iron core and winding is transferred to the transformer oil, and flows through the tank wall, convective heat transfer with the air, and the density of the transformer oil becomes smaller after heating, the transformer oil will continue to move upward, resulting in a lower temperature at the end of the winding. At the same time, considering that the low-voltage winding is located in the innermost part of the winding, the heat dissipation effect is worse than that of the high-voltage winding, so the overall temperature rise of the low-voltage winding is the highest.

3.6. Flow field simulation

The distribution of transformer flow field is shown in Fig.5, where the maximum flow rate is 0.62m/s, which is mainly distributed near the A-phase coil and has obvious eddy current phenomenon.

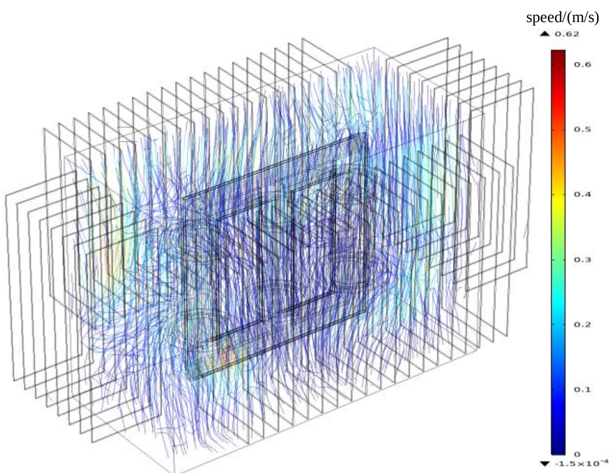

Figure 5. Flow Distribution of Transformer

From the flow field distribution, it can be seen that after the iron core and winding generate heat, the oil at the bottom of the transformer oil tank flows into the top layer through the influence of thermal floating lift, forming part of the eddy current. The transformer oil at the top of the rear oil tank flows into the heat sink for cooling treatment, and finally flows to the bottom of the transformer oil tank through the heat sink.

3.7. Mesh Independence Study

At the same time, mesh independence study is carried out, and hot spot temperatures with different numbers of meshes are given in Table 4. Considering the calculation accuracy and calculation speed, it can be inferred that when the number of nodes is 871825, the temperature rise reaches a stable value.

Table 4 The hot spot temperature under different meshes

Number of nodes	52851	365104	574421	871825
T_{max}/□	115.2	115.6	115.9	116.0

4. Oil Immersed Transformer Windings and Heat Sinks Optimization

In order to reduce the hot spot temperature of the transformer and maintain the safe and stable operation of the transformer, this paper optimizes the structure of the transformer from the inside out, including optimizing the structural parameters of the winding and attaching a cooling module to the external heat sink of the transformer tank to obtain the optimal heat dissipation configuration.

4.1. Winding optimization

Based on the analysis in section 2.5, the maximum temperature distribution of the transformer is mainly concentrated in the winding region. Therefore, in order to reduce the hot spot temperature of the transformer, this paper selects the main structural parameters that may affect the temperature rise of the transformer winding according to the structural characteristics of the winding[6], which are mainly the spacing between low voltage winding and iron core, the spacing between low voltage winding and high voltage winding, the thickness of low voltage winding, the thickness of high voltage winding, the distance between the highest point of iron core and the top of the fuel tank, expressed by d_1, d_2, d_3, d_4 and h respectively which as shown in Fig.6.

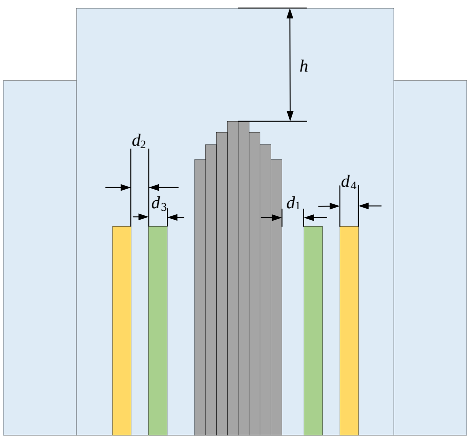

Figure 6. Structural Parameter of Windings

Among them, 5 factor levels are selected for each structural parameter, and the values of each factor level are shown in Table 5.

Table 5 Values of Factor Level

Factor level	Experimental factor				
	d_1/mm	d_2/mm	d_3/mm	d_4/mm	h/mm
1	58	21	36	48	217
2	60	23	38	50	227
3	62	25	40	52	237
4	64	27	42	54	247
5	66	29	44	56	257

In the study of complex problems with multiple factors, the central composite design method is usually used to establish the experimental table. This method can test the influence of different types of factors respectively on the premise of ensuring the number of samples, and has the advantages of simple and efficient, convenient use and effective results. In this paper, the central composite design method is used to establish a test table with 5 factors and 5 levels, and the temperature distribution of the transformer under different winding structure parameters is obtained through simulation calculation, as shown in Table 6.

Table 6 Hot Spot Temperature of Transformer under Different Structural Parameters

Test number	d_1/mm	d_2/mm	d_3/mm	d_4/mm	h/mm	T_{max}/℃
1	1	1	1	1	1	116.0
2	1	2	2	2	4	162.0
3	1	3	3	3	2	95.5
4	1	4	4	4	5	84.9
5	1	5	5	5	3	82.1
6	2	1	4	5	4	122.0
7	2	2	5	1	2	123.0
8	2	3	1	2	5	83.3
9	2	4	2	3	3	78.9
10	2	5	3	4	1	88.2
11	3	1	2	4	2	156.0
12	3	2	3	5	5	97.4
13	3	3	4	1	3	90.3
14	3	4	5	2	1	89.5
15	3	5	1	3	4	79.1
16	4	1	5	3	5	84.4
17	4	2	1	4	3	78.9
18	4	3	2	5	1	80.7
19	4	4	3	1	4	82.0
20	4	5	4	2	2	102.0
21	5	1	3	2	3	87.4
22	5	2	4	3	1	93.2

23	5	3	5	4	4	119.0
24	5	4	1	5	2	84.4
25	5	5	2	1	5	109.0

It can be seen from Table 6 that the hot spot temperature of the transformer is the highest 162.0℃ and the lowest 78.9℃. The results show that different winding structure parameters will have a certain impact on the temperature rise of the transformer. In order to obtain the optimal winding structure parameters, the range analysis method is used to study the above simulation results.

Range analysis is a method to analyze data by comparing the range size. As a measure of data, range analysis can directly reflect the range of data and show the range of data. In this experiment, the influence degree of various factors on the variation of hot spot temperature of transformer can be obtained by range analysis.

In order to obtain the degree of influence of winding structure parameters on transformer hot spot temperature, the range analysis results are shown in Table 7.

Table 7 Results of Range analysis

Test number	d_1	d_2	d_3	d_4	h
PS_1	108.1	113.16	88.34	104.06	93.52
PS_2	99.08	110.9	117.32	104.84	112.18
PS_3	102.46	93.76	90.1	86.22	83.52
PS_4	85.6	83.94	98.48	105.4	112.82
PS_5	98.6	92.08	99.6	93.32	91.8
R_j	24.82	18.24	18.94	28.88	7.8
Co_j	0.252	0.185	0.192	0.292	0.079

The formula for calculating the range R_j of each parameter is as follows:

$$R_j = \max\left(PS_a\right) - \min\left(PS_a\right), a = 1,2,3,4,5 \tag{5}$$

In the formula: PSa is the performance statistic. For example, the performance statistic PS1 of d1 is the average hot spot temperature obtained by the five simulation groups of d1 with factor level 1.

The calculation formula of contribution rate Co_j is as follows:

$$Co_j = \frac{R_j}{\sum_{j=1}^{5} R_j} \tag{6}$$

It can be seen from Table 7 that d_4 has the greatest impact on transformer hot spot temperature, with a contribution rate of 29.2%. The contribution rate of h is only 7.9%. The order of the influence degree of the five structural parameters on the transformer hot spot temperature is $d_4 > d_1 > d_3 > d_2 > h$.

Comparing the performance statistics and the contribution rate of each parameter can obtain the structural parameters that minimize the hot spot temperature of the transformer, as shown in Table 8.

Table 8 Results of Range analysis

Structural parameter	d_1	d_2	d_3	d_4	h
Value/mm	64	27	36	52	237

A new set of structural parameter combinations that did not appear in the test table was obtained by center composite design method and range analysis method. Through the simulation calculation of the temperature field of the new combination, the calculation results of the overall temperature distribution of the transformer are shown in Fig.7.

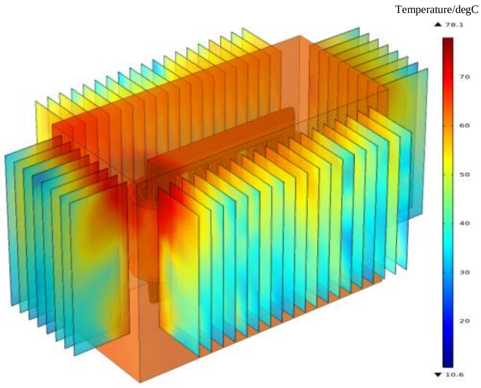

Figure 7. Overall Temperature Distribution of Transformer after Windings Optimization

It can be seen from the figure that the hot spot temperature of the transformer after winding optimization is 78.1℃, which is 37.9℃ lower than that before optimization.

4.2. Winding optimization

After winding optimization, the hot spot temperature of the transformer under normal working conditions is 78.1℃. In order to further reduce the temperature of the transformer, a cooling module is attached to the heat sink to increase the heat dissipation area[9], thus strengthening the heat dissipation effect of the oil-immersed transformer and achieving the purpose of reducing the hot spot temperature of the transformer to protect the normal operation of the transformer. The cooling module material is aluminum plate, the specific material data is shown in Table 9.

Table 9 Material Property Settings

Material	Features	Value
Cooling module (aluminum)	thermal conductivity /($W \cdot m^{-1} \cdot K^{-1}$)	237
	specific heat volume /($J \cdot kg^{-1} \cdot K^{-1}$)	903
	density /($kg.m^{-3}$)	2702

4.2.1 Selection of cooling module shape

Considering the different heat dissipation degree of cooling modules with different shapes, this paper chooses three common shapes for comparison, namely rectangle, square and fin shape, as shown in Fig.8.

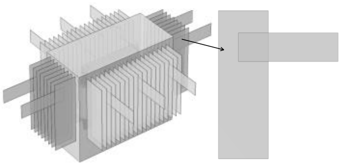

Figure 8 (a). Rectangle

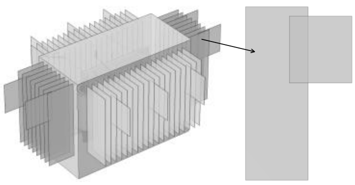

Figure 8 (b). Square

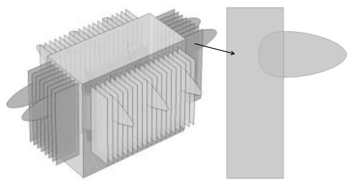

Figure 8 (c). Fin shape

The area of the cooling modules with these three shapes is $0.25m^2$, and they are installed on the heat sink in a ratio of 3:7, that is, 30% of the whole cooling module is attached to the heat sink, and the remaining 70% is exposed to the air, as shown in Fig.9.

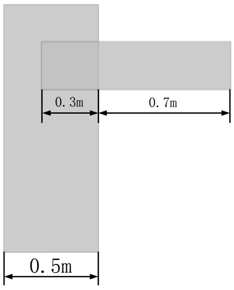

Figure 9 (a). Rectangle

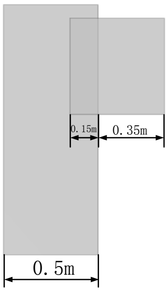

Figure 9 (b). Square

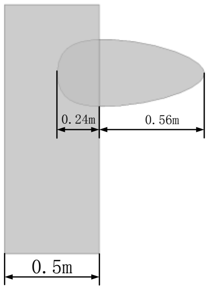

Figure 9 (c). Fin shape

The temperature field simulation calculation was carried out for transformers with cooling modules of different shapes, and the temperature distribution results were compared to select the cooling module shape with the best heat dissipation effect, as shown in Fig.10.

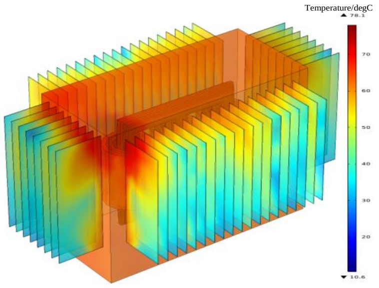

Figure 10 (a). Temperature distribution of transformer without cooling module

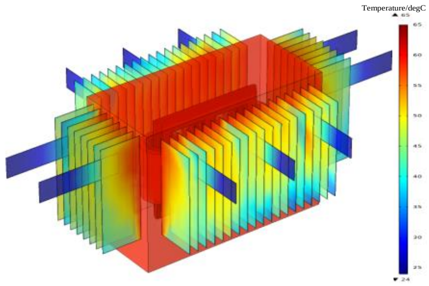

Figure 10 (b). Overall temperature distribution of transformer when the cooling module is rectangular

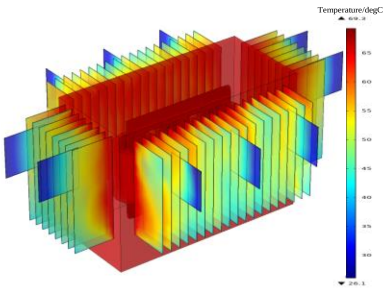

Figure 10 (c). Overall temperature distribution of transformer when cooling module is square

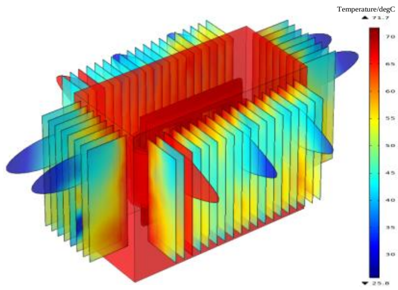

Figure 10 (d). Overall temperature distribution of transformer when cooling module is fin

As can be seen from Fig.10, when the temperature reaches a stable state, among the three selected cooling modules, when the rectangular cooling module is installed, the transformer hot spot temperature is the lowest, which is 65.0℃. Compared with that when the cooling module is not installed, the transformer hot spot temperature decreases by 13.1℃, and the heat dissipation effect is the best. Therefore, rectangle is chosen as the cooling module, and the subsequent research is based on this basis.

Fig.11 shows the temperature distribution between the heat sink with a cooling module installed and the adjacent heat sink without a cooling module installed.

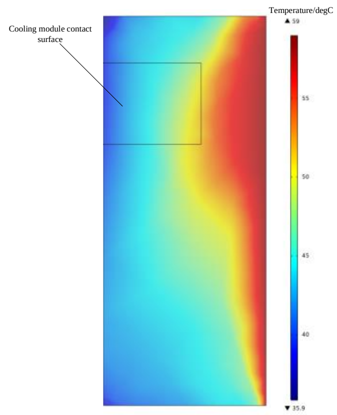

Figure 11 (a). Temperature distribution of the heat sink for installing a cooling module

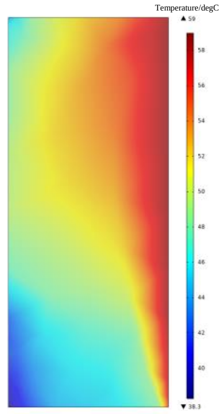

Figure 11 (b). The temperature distribution of the heat sink without the cooling module

By comparing Fig. 11 (a) and Fig. 11 (b), it can be seen that the installation of cooling module has a better cooling effect on the external surface of the transformer and the heat sink, and the temperature of the contact surface between the cooling module and the heat sink is the lowest.

4.2.2 Selection of cooling module installation position

Considering that cooling modules have different heat dissipation effects when installed in different parts, the same number of rectangular cooling modules are installed on the upper, middle and lower parts of the heat sink in the same installation mode, and the temperature field simulation is carried out respectively. The temperature distribution results are shown in Fig. 12.

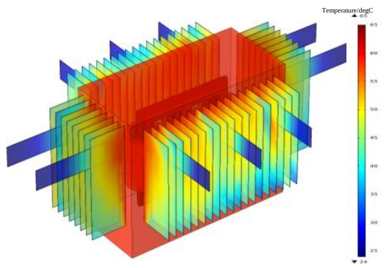

Figure 12 (a). Overall temperature distribution of the transformer when the cooling module is installed in the upper part

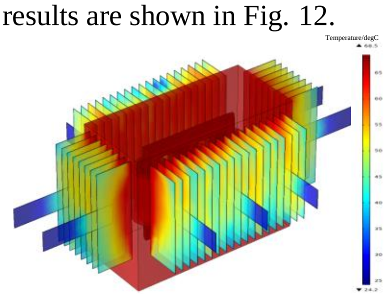

Figure 12 (b). Overall temperature distribution of the transformer when the cooling module is installed in the middle

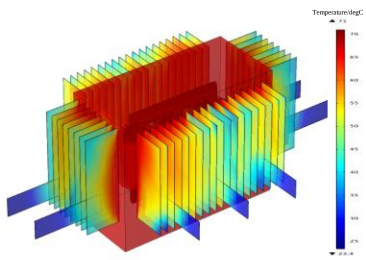

Figure 12 (c). Overall temperature distribution of the transformer when the cooling module is installed at the lower part

As can be seen from Fig. 12, when the rectangular cooling module is installed in the upper part, the heat dissipation effect is better than that installed in the middle and lower part, and the hot spot temperature of the transformer is the lowest, 65.0℃.

Based on the above research, the same amount of heat dissipation modules were installed on the upper part of the heat sink in symmetrical and asymmetric ways, and the temperature field simulation was carried out, and the results were shown in Fig. 13.

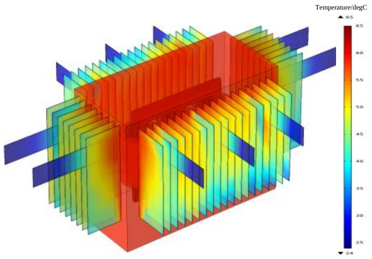

Figure 13 (a). Overall temperature distribution of transformer when cooling module is installed symmetrically

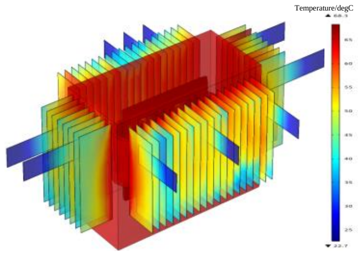

Figure 13 (b). Overall temperature distribution of the transformer when cooling module is installed asymmetrically

It can be seen from Fig. 13 that a rectangular cooling module installed symmetrically at the upper end of the heat sink has a better heat dissipation effect than an asymmetric one, and the hot spot temperature of the transformer is the lowest.

When a rectangular cooling module is symmetrically installed at the upper end of the heat sink, the oil flow velocity distribution of the y-z section of the oil-immersed transformer is shown in Fig. 14, and it can be seen from the distribution diagram that the transformer oil flow velocity at the upper part of the oil tank is the fastest.

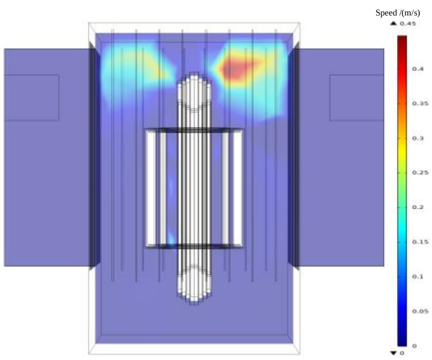

Figure 14. Oil velocity distribution in transformer section

Overall, the rectangular cooling module is best dissipated when it is symmetrically installed in an area with high surface temperature and high oil flow velocity nearby.

4.2.3 Selection of cooling module installation number

According to the above obtained cooling module installation structure and conditions to obtain the best heat dissipation effect, the cooling modules are symmetrically installed on the upper part of the transformer heat sink, and the number increases from 0 to all the cooling modules are installed on the heat sink, that is, 52 pieces. Through the temperature field simulation calculation of transformers installed with different number of cooling modules, the transformer temperature distribution law is obtained, and the hot spot temperature variation trend is shown in the figure below.

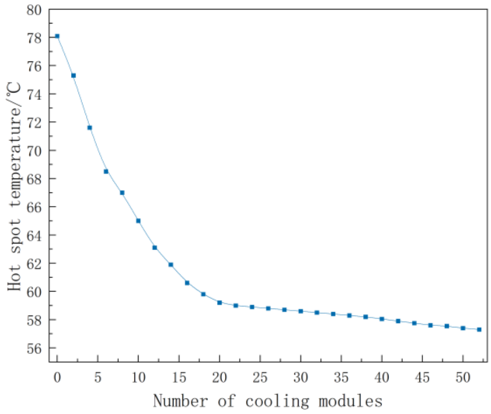

Figure 15. Trend of Transformer Hot Spot Temperature Change

It can be seen from Fig. 15 that the hot spot temperature of the oil-immersed transformer decreases with the increase of the number of cooling modules installed. Before the installation of 16 pieces, the hot spot temperature of the transformer decreases significantly with the increase of the number of cooling modules, and then the decreasing trend of temperature gradually slows down until all cooling modules are installed on the heat sink, and the hot spot temperature of the transformer reaches the lowest, 57.3℃.

Based on the winding structure parameters obtained from winding optimization, the final installation plan is to install 16 rectangular cooling modules symmetrically around the upper end of the external heat sink of the oil-immersed transformer to further reduce the hot spot temperature. The specific installation form and transformer temperature distribution are shown in Fig. 16. At this time, the hot spot temperature of the transformer is 60.7 ° C.

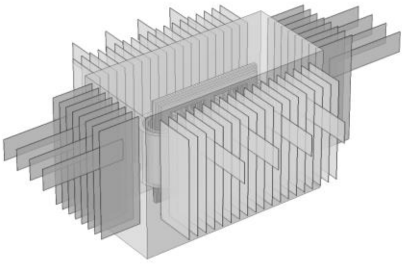

Figure 16 (a). Optimal installation structure

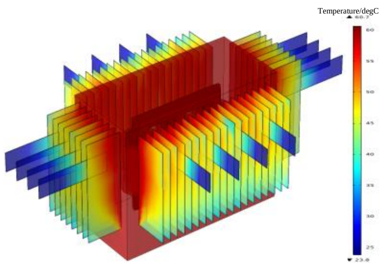

Figure 16 (b). Transformer temperature distribution

5. Conclusion

Firstly, a 3D circuit magnetic field simulation model is established according to the structure parameters of the transformer, and the core loss and winding loss of the transformer are calculated accurately. The calculated loss is loaded into the simulation model of the flow temperature field. Different from previous studies, the convection heat transfer coefficient formula in the heat convection theory is used in this paper to calculate the convection heat transfer coefficient of each wall of the transformer oil tank and the radiator, so that the distribution characteristics of the temperature field and flow field of the transformer core and winding can be obtained more accurately. The highest temperature of the transformer is located at the connection between the tank wall and the radiator, and its value is 116.0℃. The maximum flow velocity is mainly distributed near the A-phase coil, and its value is 0.62m/s. Moreover, the temperature of the A-phase winding is higher than that of the other two winding, so the eddy current phenomenon near the A-phase winding is also more obvious.

Secondly, in order to reduce the hot spot temperature of the oil-immersed transformer, the central composite design method and range analysis are used to optimize the relevant parameters of the transformer winding, and the transformer winding parameters with optimization effect on the hot spot temperature are obtained. The results show that the winding optimization scheme has a remarkable effect on reducing the hot spot temperature of the transformer.

Finally, in order to further reduce the transformer hot spot temperature, according to the principle of enhanced heat dissipation, a cooling module is attached to the external radiator of the transformer to reduce the transformer hot spot temperature. Through finite element simulation, the influence of different shapes, different installation positions, different installation modes and different number of cooling modules on the hot spot temperature of the transformer is analyzed, and the optimal installation structure is obtained. By installing an optimized cooling module structure, the temperature was reduced by 22.3% compared to the initial temperature. The experiment shows that the optimization scheme can effectively reduce the hot spot temperature of the oil-immersed transformer, and provides a theoretical basis for reducing the hot spot temperature of the transformer, improving the heat dissipation performance of the transformer, and ensuring the safe and stable operation of the transformer.

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Nomenclature

$\vec{B}$ — Magnetic flux density, [T]
C_p — Specific heat capacity at constant pressure, [J·Kg^{-1}·K^{-1}]
$\vec{D}$ — Electric displacement vector, [C·m^{2}]
$\vec{E}$ — Electric field strength, [V·m^{-1}]
f — External force density vector, [N·m^{3}]
$\vec{H}$ — Magnetic field strength, [A·m^{-1}]
h — Thermal conductivity, [W·m^{-1}·K^{-1}]
$\vec{J}$ — Current density, [A·m^{-2}]
p — Internal pressure of the fluid, [Pa]
q_s — Heat flux, [W·m^{-2}]
S_T — Heat source, [W·m^{-3}]
T_a — Ambient temperature, [K]
u — Oil flow velocity vector, [m·s^{-1}]
u_0 — Boundary component of the oil flow velocity vector, [m·s^{-1}]

Greek symbols

ε — Dielectric constant, [F·m^{-1}]
η — Hydrodynamic viscosity coefficient, [N·s^{-1}·m^{-2}]
λ — Thermal conductivity, [W·m^{-1}·K^{-1}]
μ — Permeability, [H·m^{-1}]
σ — Conductivity, [S·m^{-1}]
ω — Vorticity, [s]

References

[1] Shen W.K., Research on Heat Transfer Performance of Large Oil Immersed Natural Ester Oil Transformer, Hebei University of Science and Technology, Shijiazhuang, China, 2023.

[2] Wang Y.Q., et al., Calculation of 3D Temperature Field of Oil Immersed Transformer by the Combination of the Finite Element and Finite Volume Method, *High Voltage Engineering*, *40* (2014), 10, pp. 3179-3185.

[3] Laidoudi, et al., Natural-convection of Newtonian fluids between two concentric cylinders of a special cross-sectional form, *Thermal Science, 25* (2020), pp. 190-190.

[4] Yuan F.T., et al., Temperature Characteristic Analysis and Radiator Optimization of Oil-immersed Transformer Based on Multi-physical Field Simulation, *High Voltage Engineering*, *50* (2019), 01, pp. 221-231.

[5] Laidoudi, et al., The Effect of Asymmetrically Confined Circular Cylinder and Opposing Buoyancy on Fluid Flow and Heat Transfer, *Defect and Diffusion Forum*, *374* (2017), pp. 18-28.

[6] Yuan F.T., et al., Heat Dissipation Performance Analysis and Structural Parameter Optimization of Oil-immersed Transformer based on Flow-thermal Coupling Finite Element Method, *Thermal Science*, *26* (2022), 04, pp. 3241–3253.

[7] Houssem, et al., The Effects of Aiding and Opposing Thermal Buoyancy on Downward Flow around a Confined Circular Cylinder, *Periodica Polytechnica*, *Mechanical Engineering*, *62* (2017), 01, pp. 42-50.

[8] Houssem, et al., Natural Convection from Four Circular Cylinders in Across Arrangement within Horizontal Annular Space, *Acta Mechanica et Automatica*, *14* (2020), 02, pp. 42-50.

[9] Tang Z.J., et al., Influence of External Cooling Modules on Hot‐spot Temperature Rise of Distribution Transformer, *High Voltage Apparatus*, *60* (2024), 03, pp. 135-143.

[10] Li Y.F., Multi-factor Integrated Heat dissipation Optimization Analysis of dry-type Transformer, *China Electrical Equipment Industry* ,(2023), 03, pp. 45-47+68.

[11] Cheng H., et al., Design of a new distribution transformer high temperature uniform insulation, *Equipment Management and Maintenance*, (2023), 06, pp. 92-93.

[12] Zhou H.B., et al., Calculation and Analysis of Winding Hot-point Temperature in Different Loads of Dry-type Transformer, *Transformer*, *59* (2022), 01, pp. 1-5+21.

[13] Jiang H.Z., et al., Study on Radiator Arrangement of Split Oil-Immersed Self-Cooling Transformer, *Transformer*, *56* (2019), 03, pp. 45-49.

[14] Liu Z., Research on Temperature Rise Characteristics Under Different Operating Conditions of Oil-immersed Transformers based on Multi-physics Fields, Shenyang University of Technology, Shenyang, China, 2023.

[15] Smolka, J., CFD-based 3-D optimization of the mutual coil configuration for the effective cooling of an electrical transformer. Applied Thermal Engineering, *50* (2013), 01, pp. 124–133.

[16] Yuan F.T., et al., Temperature Rise Calculation and Structure Optimization Re-search of Transformer Winding Based on Electromagnetic-fluid-thermal Coupling, *High Voltage Engineering*, *50* (2020), 03, pp. 952-961.

[17] Shi F.L., Influence of Oil Collection Pipe with Different Angles on Heat Dissipation Effect of Transformer, *Automation Application*, *65* (2018), 02, pp. 116-117+123.

[18] Duan C.H., et al., Study on equivalent method of boundary radiation-convection heat transfer for transformer temperature field calculation, *Electric Machines and Control*, *20* (2024), 10, pp. 120-129.

[19] Ni G.K., et al., Optimal Design of High Overload Distribution Transformer, *New Technology & New Products of China*, *23* (2019), pp. 58-59.

[20] Jin, Y., et al., Heat Dissipation Optimization Design of Epoxy Resin Sealing High Frequency Transformer, *Power System Technology*, *46* (2022), 07, pp. 2531-2537.

[21] Wang X.D., Heat dissipation optimization Analysis of Oil-immersed Transformer based on SolidWorks Flow Simulation, *Digital Manufacturing Industry*, (2012), 07, pp. 68-70.

[22] Li, H., et al., Theoretical Analysis and Experimental Research on Heat Dissipation of Transformer Disk-type Winding Based on Energy Flow, *Proceedings of the Chinese Society of Electrical Engineering*, *44* (2024), 08, pp. 3327–3336.

[23] Yuan F.T., et al., Coupling Simulation and Collaborative Optimization of Electromagnetic, Thermal and Structural Multi-physical Fields for Dry-type Core Reactor, *Power System Technology*, *46* (2020), 07, pp. 2823-2833.

[24] Houssem, et al., Study the effect of flow velocity and thermal buoyancy on the dynamic behavior of flow inside a two-hole chamber, *Journal of Ambient Energy*, *43* (2021), 01.

[25] Laidoudi, et al., Thermal activity of hot bodies trapped inside a moving chamber with a complex fluid under the influence of MHD and buoyancy forces, *Numerical Heat Transfer*, Part B: Fundamentals 85 (2023).

[26] Jiang X.W., et al., A fast calculation method of transformer winding temperature based on response surface methodology, *Zhejiang Electric Power*, *42* (2019), 12, pp. 20-27.

[27] Fan J.L., Integrated intelligent distribution transformer design, Dalian University of Technology, Dalian, China, 2021.

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