Error Analysis of Transformer Hot Spot Temperature Measurement

Zhengang Zhao[1,2,*], Zhengyu Yang[1], Yuyuan Wang[3], Ke Liang[1], Nengsi Jin[1], Kaiqiang Shi[1], Chuan Li[1,2] and Yingna Li[1,2]

[1]*Faculty of Information Engineering and Automation, Kunming University of Science and Technology, Kunming, Yunnan, China*
[2]*Yunnan Key Laboratory of Computer Technology Applications, Kunming, Yunnan, China*
[3]*Yunnan Institute of Measuring and Testing Technology, Kunming, Yunnan, China*
E-mail: zhaozhengang@kust.edu.cn
[*]*Corresponding Author*

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Abstract

According to the national standard GB/T 1094.7-2008, the method of hot spot measurement of oil-immersed transformer is used to place several temperature sensors inside the gasket within the predicted hot spot position to measure the temperature of winding transformer. The highest temperature measured is regarded as the hot spot temperature of transformer. Since the winding and gasket are bad conductors of heat, there exists certain temperature difference between the gasket and the hot spot temperature of the winding. This temperature difference is not mentioned in the national standard GB/T 1094.7-2008, which is bound to affect the accuracy of the transformer hot spot temperature measurement.In order to ensure safe operation of transformer, the thermal environment of temperature measuring point is analyzed and the discrete equation of boundary node is established. The parameters are set according to the heat transfer mode of the oil-immersed transformer and the temperature characteristics of each heat

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transfer node is analyzed. Gauss-Seidel Iteration method is used to calculate the theoretical value of the measuring point of the oil-immersed transformer and the heat transfer model of the measuring point is established for further analysis. The experimental platform of the oil-immersed transformer simulator is established according to the method described in the national standard and used to measure the hot spot temperature and winding surface temperature. The results show that when the winding temperature is 77°C, the heat transfer model of the temperature measuring point is 74.7°C and the experimental temperature of the temperature measuring point is 74.9°C. The relative error between theoretical calculation temperature and experimental temperature is 0.27%. As the temperature of the experiment increases, the temperature difference between the temperature point and the winding temperature gradually increases, and the maximum absolute error is 2.1°C.

Keywords: Oil immersed transformer, temperature measurement point, temperature difference, boundary node discrete equation.

1 Introduction

Large oil-immersed power transformers are an important part of power transmission and transformation system, and their safe and stable operation is the guarantee for the normal operation of the power transmission and transformation network [1]. The maximum operating temperature of the transformer is clearly specified in the oil-immersed transformer load guide. The hot spot temperature is an important indicator to measure the life and operating status of the transformer [2].

In recent years, researchers have devoted in establishing the hot spot distribution of transformer winding. In most of their works, a certain number of temperature sensors are placed separately and the range of hot sports is estimated empirically [3]. In 2012, Chen et al. used Liebenberg-Marquardt algorithm to estimate the transformer model parameters which are impacted by the temperature, and an improved model of transformer winding hot spot temperature based on top oil temperature was proposed [4]. In 2015, Wang et al. studied the equivalent heat source of hot spot temperature, and improved a calculation model of transformer hot spot temperature based on the bottom oil temperature [5]. In 2016, Yang et al. carried out a transformer hot spot temperature calculation model by determining winding time constant [6]. In their work, the sensor is installed in the gasket between the winding. with the considering that oil-immersed insulating paper and transformer gaskets are poor thermal conductors, The convection heat exchange between insulating paper and transformer oil will cause certain errors in the measurement of winding hot spot temperature [7].

At present, in the research on the hot spot distribution of transformer winding, most of the researchers according to the hot spot temperature measurement method described in the national standard GB/T 1094.7-2008, empirically estimated the range of hot spots, and place a certain number of temperature sensors separately inside the gasket within the estimated range [8]. Considering that oil-impregnated insulating paper and transformer gasket are bad conductors of heat, contact thermal resistance of oil-impregnated insulating paper and winding, thermal resistance of oil-impregnated insulating paper, thermal resistance of transformer gasket, and convection of insulating paper and transformer oil will inevitably lead to errors in measuring the temperature of winding hot spot. According to the 6-degree rule, the influence of this measurement error on the assessment of transformer insulation life can not be ignored. In order to establish a more accurate life evaluation model for oil-immersed transformers, the temperature difference between the temperature measurement point of the oil-immersed transformer gasket and the actual winding temperature was studied.In this paper, the heat transfer model based on the boundary node discrete equation is established by analyzing the heating conditions of the temperature measuring point of the gasket. The Gauss-Seidel iteration method is used to calculate the theoretical value of the temperature measurement point of the oil-immersed transformer, and the relationship between the temperature measurement point of the gasket and the temperature of the winding is obtained. According to the oil immersed transformer simulation experiment device, the heat transfer model parameter values are set, and the theoretical temperature value of the temperature measurement point is calculated and compared with the experimental data. Finally, the trend of the temperature difference between the temperature of the temperature measurement points and the hot spot temperature of the winding changes in the temperature of the winding is analyzed [9].

2 Methods

The error between the inner temperature of the gasket and the actual temperature of the winding is analyzed through mathematical model and simulation experiment in this section.

2.1 Heat Transfer Model

In large oil-immersed transformers, the multi-cake winding is placed on the same core, and each pie winding is separated by a plurality of spacers [10] as shown in Figure 1.

Considering that the transformer gasket is a rectangular material of smaller thickness (wide 15 mm, Height 2 mm),during the transfer process, the heat flow can only spontaneously flow from a higher temperature point to a lower temperature point. Since the transformer winding has a small thickness of a circular pie shape, the horizontal transfer of the heat flow can be ignored inside the winding [11]. In the steady-state environment, the heat flux density of each heat transfer section in the vertical direction is equal [12]. refer to the position of the gasket in the transformer,The gasket is heated in the transformer as shown in the Figure 2.

As can be seen in Figure 2, the upper and lower sides of the gasket are in contact with the insulating paper, and the left and right sides are in contact

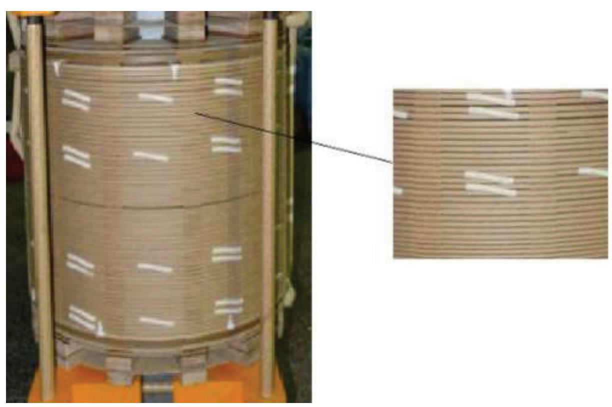

Figure 1 Transformer winding diagram.

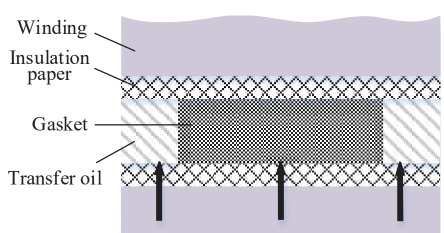

Figure 2 Schematic diagram of gasket thermal analysis.

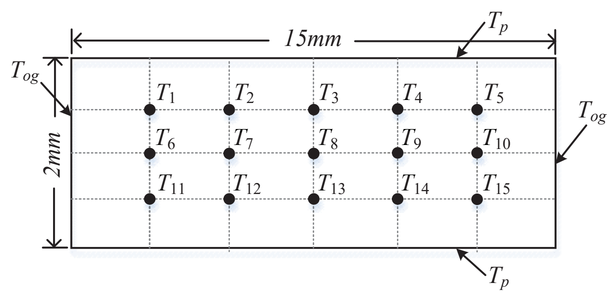

Figure 3 Schematic diagram of mesh generation.

with the transformer oil. Since the heat transfer process including the gasket is complicated, and it is difficult to perform accurate heat analysis of the gasket [13]. Therefore, the mutual influence between the surface temperature of the insulating paper and the temperature of the transformer oil is ignored. It is considered that the surface temperature of the four heating surfaces of the gasket is equal to the surface temperature of the object in contact with it, and then an ideal heating model of the gasket is established. The heat model taking into account factors such as accuracy and computational efficiency, using Δx = 2.5 mm, Δy = 0.5 mm the grid, divides and sets up multiple temperature nodes. As shown in Figure 3, Where T_p is the surface temperature of the insulating paper in the direction of the horizontal oil channel, T_{og} is the temperature of the transformer oil on both sides of the gasket surface, T_1 to T_{15} is the temperature node of the mesh.

The temperature of the temperature measurement point is calculated by the Gauss-Seidel iterative method. According to Figure 3, the relationship between each node is:

$$\begin{cases} T_1 = \dfrac{T_{og} + T_p + T_2 + T_6}{4} \\ T_2 = \dfrac{T_2 + T_p + T_3 + T_7}{4} \\ \qquad \vdots \\ T_{14} = \dfrac{T_{13} + T_9 + T_{15} + T_P}{4} \\ T_1 = \dfrac{T_{14} + T_{10} + T_{\mathrm{og}} + T_P}{4} \end{cases} \tag{1}$$

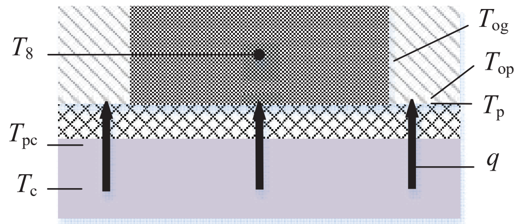

Figure 4 Heat transfer model.

where the temperature of the grid node T_8 is the temperature of the gasket temperature measurement point.

The winding are distributed around the iron core and superimposed on each other like the longitudinal direction of the round cake. During the winding stacking process, a gap is left in each pie-shaped winding to facilitate the flow of oil in the transformer for heat dissipation [14], but at the same time it will make the winding temperature distribution uneven. During the transfer process, the heat flow can only spontaneously flow from a higher temperature point of a lower temperature point. Since the transformer winding is in the shape of a disc with a small thickness, the horizontal transfer of heat flux inside the winding can be ignored. It is considered that all heat flux is transferred in the upper and lower directions perpendicular to the winding. The heat flux density of each heat transfer segment in a steady-state environment is equal. Since the gap between the adjacent cakes of the winding is relatively small, and the temperature distribution of the adjacent winding is continuously changed. The Riemann integral sampling and segmentation method is used to evenly divide the entire winding height interval into several sub-intervals of equal length, adjacent winding can be used as a sub-interval, and then the same criterion can be used to obtain the point on each sub-interval to which the adjacent winding temperatures are approximately equal.

According to the installation structure near the gasket, the heat transfer model can be obtained as shown in Figure 4. Heat flow is transferred outward from the surface of the winding and flows through the insulating paper into the gasket or the transformer oil.

where the surface temperature T_p of the insulating paper in the direction of the oil channel is considered to be equal within a small range whether it is contact with the transformer oil or the gasket, and the temperature T_{og} of the transformer oil at the surface of the gasket is equal to the temperature T_{op} of the transformer oil on the surface of the insulating paper.

Since the cross section of the gasket is relatively wide and short rectangular, the influence of the gasket on heat flow direction is mainly concentrated on the intersection of the gasket, the insulating paper surface and the transformer oil. It will not greatly affect the temperature around the gasket. Therefore, the influence of the gasket on the direction of heat flow is ignored in the study of this paper. According to the heat transfer model, the temperature nodes of the heat transfer process are shown in Figure 5:

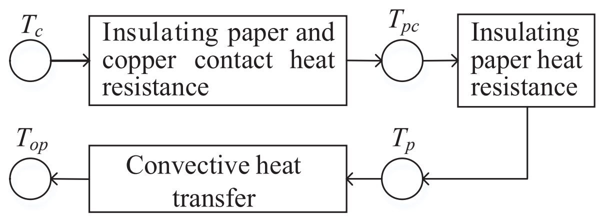

Figure 5 The temperature node relationship of the heat transfer process.

The relationship between temperature difference, heat flux density, thermal resistance per unit area, contact resistance per unit area, and convective heat transfer coefficient is:

$$q = \frac{\Delta T}{R} \tag{2}$$

$$q = \frac{\Delta T \cdot \lambda}{\delta} \tag{3}$$

$$q = h \cdot \Delta T \tag{4}$$

where q(W/m^2) is the heat flux density, ΔT(°C) is the temperature difference of the adjacent node temperature, and R(m^2·K/W) is the thermal resistance of the oil-immersed insulating paper to the unit area of the winding at this temperature. δ(m) is the thickness of the insulating paper, and λ(W/m·K) is the thermal conductivity of the oil-impregnated insulating paper at this temperature, h(W/m^2·K) is the thermal convective heat transfer coefficient of transformer oil on the surface of insulating paper, and its calculation formula is [15]:

$$\begin{cases} h = C_1 \left(\dfrac{\Delta\theta_{hs}}{\mu_{hs}} \right)^n \\ C_1 = C[L^{(3n-1)/n} K^{(1-n)/n} C_{oil} \rho^2 g \alpha]^n \end{cases} \tag{5}$$

Table 1 Physical parameters of transformer oil

Physical Property	Fitting Formula
Fitting formula (kg/m^3)	$\rho = -0.58$T+893.09
Power viscosity (kg/mg·s)	$\mu_{hs} = 8 \times 10^{-5}\mathrm{T}^2 - 4.8 \times 10^{-3}\mathrm{T} + 0.1$
Thermal conductivity (W/m·K)	$\mathrm{K} = -8.049 \times 10^{-5}\mathrm{T} + 0.133$
Specific heat capacity (J/kg·K)	$\mathrm{C} = 4.207\mathrm{T} + 1763.4$

where: *L*(m) is the oil convection heat dissipation surface characteristic size, *g*(9.8 m/s^2) is the neutral acceleration, *K*(m·K) is the oil thermal conductivity, ρ(kg/m^3) is the transformer oil density, α(K^{-1}) is the thermal expansion coefficient of the oil, C_{oil}(J/(kg·K)) is the specific heat capacity of the oil, μ_{hs}(kg·s^{-1}·m^{-1}) is the viscosity of the oil at operating temperature, $\Delta\theta_{hs}(^\circ\mathrm{C})$ is the temperature difference between the winding and the surrounding transformer oil [16]. The physical properties of the transformer oil vary from temperature as shown in Table 1.

In the analysis of this paper, the contact thermal resistance *R* of the insulating paper and the winding and the thermal conductivity λ of the oil-impregnated insulating paper are obtained by the steady state experiment and theoretical analysis of the double heat flow meter [17]. The relationship between the thermal resistance *R* of the insulating paper and the winding and the temperature is obtained [18], as shown in Figure 6. The relationship between the thermal conductivity λ of oil-impregnated insulating paper and temperature is shown in Figure 7.

From Equations (2), (3), and (4), it can be known that the heat transfers model can be calculated by confirming the boundary conditions of one end when the heat flux density and the heat transfer parameters of the heat transfer medium have been determined. The boundary condition can be obtained by the thermal thermocouple No. 3 installed inside the transformer. The influence of the ambient temperature and the input voltage on the boundary conditions can be taken into account in the sensor measurement temperature, so the impact of the external environment is no longer analyzed. The winding made of red copper material and transformer oil are good heat conductors, and it can be considered that the temperature of each point is equal in a small range.. Therefore, in this article, it is considered that the surface temperature T_p of the insulating paper in the horizontal oil channel direction in a small range is equal whether it is in contact with the transformer oil or the gasket. Therefore, in this study, the temperature T_{og} of transformer oil on the gasket

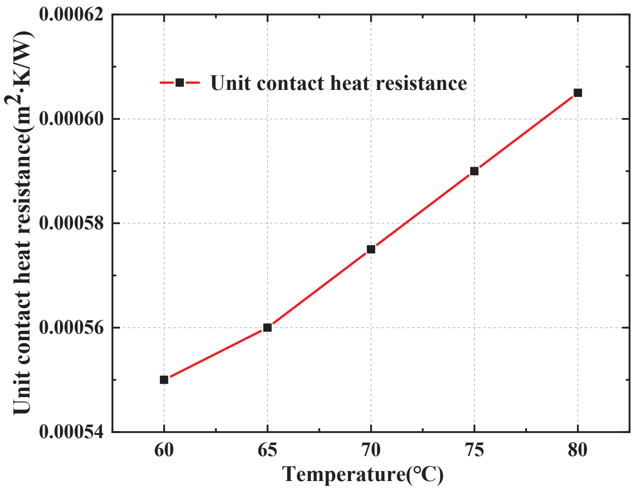

Figure 6 Relationship between thermal contact resistance and temperature.

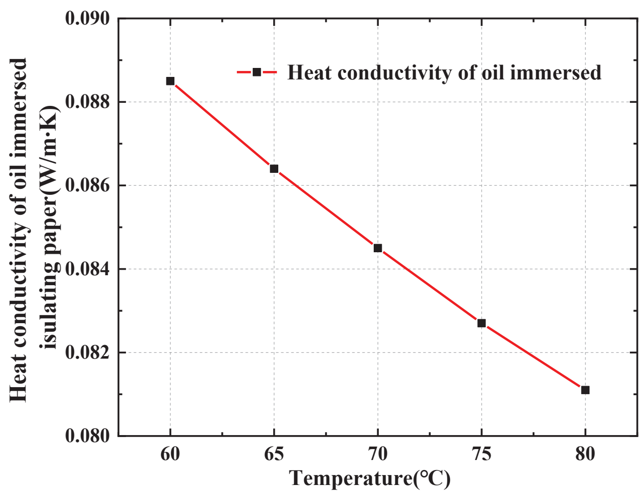

Figure 7 Relationship between thermal conductivity and temperature.

surface is equal to the temperature T_{op} of transformer oil on the surface of insulating paper [19].

The heat is transferred from the winding surface and flows through the insulating paper into the gasket or into the transformer oil. When the heat flow flows into the transformer oil or gasket, the direction of heat flow will no longer be vertical upward. The heat transfer model can be calculated by confirming the boundary conditions of one end when the heat flux density and the parameters of the model have been determined. The heat transfer model can be obtained:

$$T_p = T_c - qR - \frac{q\delta}{\lambda} \tag{6}$$

$$T_{og} = T_{op} = T_p - \frac{q}{h} \tag{7}$$

where q(W/m^2) is the heat flux density, R(m^2·K/W) is the thermal resistance of the oil-immersed insulating paper to the unit area of the winding. δ(m) is the thickness of the insulating paper, and λ(W/m·K) is the thermal conductivity of the oil-impregnated insulating paper, h(W/m^2·K) is the thermal convective heat transfer coefficient of transformer oil on the surface of insulating paper.

Based on Equations (6) and (7), the temperature T_p and T_{og} around the gasket can be calculated, and the temperature T_8 of temperature measurement point of gasket can be calculated by Gauss-Seidel iteration method.

2.2 Experiment on Gasket Temperature

The winding is made of copper tube with thermal resistance wire inside, and the outer surface of the copper tube is wrapped with two layers of insulating paper. And the thermal resistance wires of each cake winding are connected in series with each other to ensure the current passing through is equal, so that the heating power of each winding is equal. The analog winding, iron cores, and transformer shim are assembled in the same way as large oil-immersed transformers. The temperature sensor is placed on the transformer gasket, the winding outer insulation paper surface and the copper surface.

According to the parameters of the experimental device as shown in Table 2, the parameters of the theoretical analysis of the heat transfer model are set.

The WRNK-191K armored thermocouple is used in this experiment with the probe diameter of 1mm, such that it will not damage the structural performance of the transformer when being installed [20]. Four sets of sensors are placed on the winding of different heights. In order to reduce the measurement error of the surface temperature, the isothermal contact type is adopted in this work with a small measurement surface temperature error within 0.1°C [21].

Table 2 Structural parameters of transformer components

Parts	Structural Parameter
Winding	Outer diameter 237.3 mm
	Inner diameter 106.7 mm
Gasket	Wide 15 mm
	Height 2 mm
Horizontal oil channel	Height 2 mm
Heat resistance wire	Single cake resistance 32 Ω
	Total resistance 180 Ω
Insulating paper	Single thickness 0.05 mm

Due to oil flow the hot spot distribution of the oil-immersed transformer may be uneven, so the temperature measurement point of the temperature sensor needs to be as close as possible to the same temperature gradient. In this experiment, the temperature measurement points in the front section of the thermocouple are set on the same horizontal line of the same horizontal oil passage, that is, on the same copper pipe. Under the condition that the measurement does not affect each other and ensure the normal heat transfer of the transformer, the temperature measurement points of the three thermocouples are placed as close as possible to each other. As shown in Figure 8:

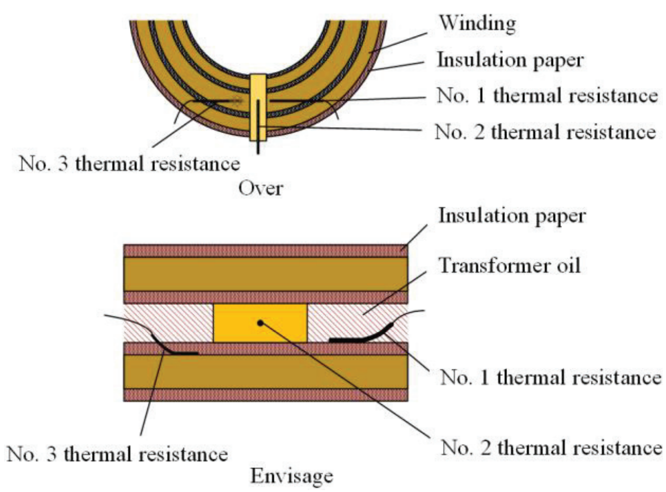

Figure 8 Sensor installation location diagram.

where the No. 1 thermocouple measures the top temperature of transformer oil on the surface of the insulating paper, and it is used to determine the transformer oil related parameters. No. 2 thermocouple measures the temperature of the temperature measuring point inside the gasket. No. 3 thermocouple measures the surface temperature of winding.

In order to ensure the safe and stable operation of the transformer, it is generally stipulated that the top oil temperature of the transformer should not exceed 85°C when the natural circulation cool transformer is running [22]. The winding temperature is controlled between 30°C and 80°C to ensure the safe and stable operation of the transformer. Finally, the steady-state data at 76V, 105V, 128V, 139V, 152V, 173V, 182V at both ends of the thermocouple wire were collected. The experiment began when the temperature change at the temperature measuring point was less than 0.1°C, and 60 sets of data were collected every minute. In order to eliminate random errors, after the data collection was completed, the power supply of the experimental device was turned off and the transformer was naturally cooled to room temperature. Then the experiment was repeated five times, and 300 sets of data were collected at each temperature measurement point to obtain the average value.

3 Results

Transformer data acquisition results are shown in Figure 9. The temperature difference becomes larger as the winding temperature increases. When the winding temperature is 77°C, the temperature difference between the temperature of the gasket temperature and the winding temperature reaches 2.1°C. Considering the influence of thermocouple surface temperature measurement error, the winding temperature sensor is installed between the surface of the winding and the insulating paper. Since the direction of heat flow flows from the winding to the insulating paper, the temperature measurement result of the winding surface will be smaller than the actual temperature, so the temperature difference between the temperature measurement point of the gasket and the temperature of the winding should be greater than 2.1°C under actual condition. According to the transformer hot spot temperature measurement method and the 6-degree rule described in the national standard GB/T 1094.7-2008, the temperature difference between the gasket measuring point and the winding copper will result in an error over 17.5% for transformer life evaluation.

It can be seen from the experimental results that the heat transfer process is affected by the contact thermal resistance of the insulating paper, the

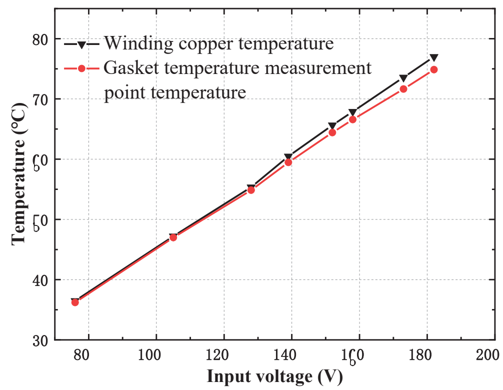

Figure 9 Temperature difference between the temperature of gasket measuring point and winding temperature.

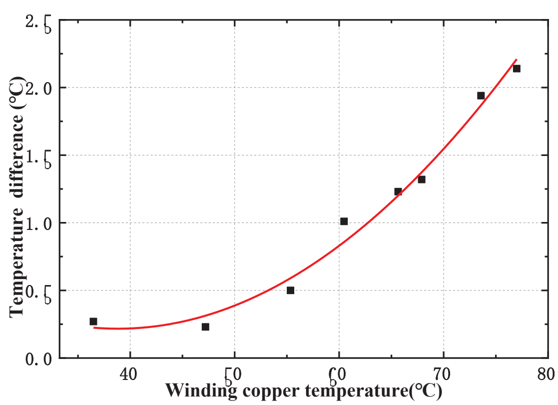

Figure 10 The temperature difference between the gasket temperature measurement point and the winding increases with the winding temperature.

thermal resistance of the insulating paper, and the convection heat transfer of the transformer oil, resulting in a relatively obvious temperature difference between the temperature measurement point temperature of the gasket and the winding temperature. The relationship between the temperature of the gasket temperature measurement point and the actual temperature difference of the winding is shown in the Figure 10.

In order to verify the accuracy of the theoretical temperature calculation of the gasket temperature measurement point, the calculation results corresponding to different temperatures are compared with the experimental measurement results of the gasket temperature measurement point in Table 3:

Table 3 Comparison between experimental value and calculated value of temperature measurement point for transformer gaskets

Input Voltage (V)	Experimental Temperature (°C)	Calculated Temperature (°C)	Winding Surface Temperature (°C)
76	36.2	36.1	36.4
105	46.9	47.3	47.2
128	54.8	54.2	55.3
139	59.4	59.7	60.4
152	64.3	64.0	65.6
158	66.5	66.1	67.9
173	71.6	71.2	73.5
182	74.9	74.7	77.0

It can be seen from Table 3 that the absolute error between the theoretical calculation temperature and the experimental temperature is within 0.6°C. This calculation method can better calculate the gasket temperature measurement point temperature through the winding temperature simulation, and the obtained temperature difference between the winding and the gasket temperature measurement point can be better used in actual calculations.

4 Discussion

According to the national standard GB/T 1094.7-2008, the method of hot spot measurement of oil-immersed transformer is used to place several temperature sensors inside the gasket within the predicted hot spot position to measure the temperature of the winding. The highest temperature measured is regarded as the hot spot temperature of the transformer. Since the winding and gasket are poor conductors of heat, there exists certain temperature difference between the gasket and the hot spot temperature.

In this work, the heat transfer process of the gasket temperature measurement point is analyzed by studying the heat condition. The heat transfer model of the gasket temperature measurement point is built, as well as the transformer simulation device. The theoretical analysis is verified by experiments. The temperature difference between the gasket temperature measurement point and the winding temperature increases with the winding temperature. This calculation method can estimate the temperature of the gasket by simulation of the winding temperature, such that the temperature difference between the winding and the temperature measurement point of the gasket can be obtained.

5 Conclusions

The results show that there is a large temperature difference between the temperature measurement point of the gasket and the copper of the winding, and the temperature difference becomes larger as the temperature of the winding copper increases. At 77°C, the temperature difference between the temperature measurement point of the gasket and the winding reached 2.1°C. According to the national standard GB/T 1094.7-2008, the transformer hot spot temperature measurement method and the 6-degree rule, the temperature difference between the gasket temperature measurement point and the winding copper will cause an error of 17.5% in the transformer insulation service life assessment, and according to thermal analysis, the error of transformer life assessment is higher than 17.5% under real conditions. This provides data support and theoretical guidance for the subsequent establishment of temperature models and life assessment of transformer winding.

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Biographies

Zhengang Zhao received his Bachelor degree in Electronic Science and Technology, Master degree in Microelectronics and Solid State Electronics, and Ph.D. degree in Microelectronics and Solid State Electronics from Harbin Institute of Technology, Harbin, China, in 2005, 2007 and 2012, respectively. He is currently an associate professor in the faculty of Information Engineering and Automation at Kunming University of Science and Technology. He has authored or coauthored over 30 papers in major journals. His current research interests include Optical Fiber Sensing technology and Cyber-Physics Systems modeling.

Zhengyu Yang is a master student of control engineering, School of Information Engineering and Automation, Kunming University of Science and Technology. Graduated from North China Electric Power University, majoring in automation, with a bachelor's degree in 2019. Since my master's degree, I have been engaged in the research of transformer temperature rise, electric energy measurement, data analysis and other issues. It has a deeper understanding of the research status, development trends and existing problems in the field of electric power.

Yuyuan Wang, born in 1965 in Yunnan, China, graduated from Yunnan Normal University with a bachelor's degree in physics in 1987. In 2003, he obtained the qualification of senior engineer. Mainly engaged in electrical metrology, measurement technology and method research, laboratory technology management, etc.

Ke Liang was born in Henan, China in 1996.He received his Bachelor's degree in automation from SIAS International College of Zhengzhou University in 2018. He is currently pursuing the Master of Measurement Technology and Instrument in Kunming University of Science and Technology. His research interests includes hot spot temperature of power equipment and thermal characteristics of insulating materials.

Nengsi Jin was born in Yunnan, China in 1994.He received his Bachelor's degree in automation from Yuxi Normal University in 2017. Then he received the Master's degree of Control Engineering in Kunming University of Science and Technology in 2020. His research interests includes insulation and transformer temperature monitoring of high-voltage electrical appliances.

Kaiqiang Shi was born in Shandong, China in 1992. He received his Bachelor's degree in measurement and control technology and instrumentation from Changchun University of Technology in 2015. Then he received the Master's degree of Detection Technology and Automatic Equipment in Kunming University of Science and Technology in 2019. His research interests includes the spatial temperature distribution of oil-immersed transformers.

Chuan Li, born in 1971, received his doctorate degree in optical engineering from Tianjin University in 2002. On September 18, 2002, he was awarded the 2001 Wang Daheng Award of Chinese Optical Society. In 2008, he was awarded the Academic and Technical Leader of Yunnan Province. At present, he is a professor and doctoral supervisor at Kunming University of Science and Technology, and the chief professor of Information Detection and Processing Innovation Team. His main research interests are sensor development and detection applications.

Yingna Li graduated from the Department of Computer Science and Technology, Yunnan University in 1996, majoring in software engineering. In 2005, he went to UNBC to study bilingual teaching in computer science. In 2009, he obtained the master's degree of computer application technology in our university. He is mainly engaged in sensor network construction, information integration and intelligent analysis.