Effect of Loads on Temperature Distribution Characteristics of Oil-Immersed Transformer Winding

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Abstract

The temperature of the hot-spots on windings is a crucial factor that can limit the overload capacity of the transformer. Few studies consider the impact of the load on the hot-spot when studying the hot-spot temperature and its location. In this paper, a thermal circuit model based on the thermoelectric analogy method is built to simulate the transformer winding and transformer oil temperature distribution. The hot-spot temperature and its location under different loads are qualitatively analyzed, and the hot-spot location is analyzed and compared to the experimental results. The results show that the hot-spot position on the winding under the rated power appears at 85.88% of the winding height, and the hot-spot position of the winding moves down by 5% in turn at 1.3, 1.48, and 1.73 times the rated power respectively.

Keywords: Oil-immersed transformer, winding hot-spot, thermoelectric analogy, thermal model, transformer simulation device.

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1 Introduction

The oil-immersed transformer is an essential part of power transportation, and its operation stability will impact the reliability and operating cost of the grid system (Hong et al.; Hamzeh et al., 2015). The hot-spot temperature and hot-spot position of the oil-immersed transformer are important monitoring targets for regular transformer operation. In order to ensure the safe and stable operation of the transformer, real-time monitoring and prediction are required for the hot-spot temperature during the operating (Taheri et al., 2019; Pylvanainen et al., 2007; Chochowski and Obstawski, 2017). In this regard, SwiftG et al. (2001) proposed to use the analog thermoelectric method to establish a transformer temperature calculation model. The analog thermoelectric method gradually becomes a standard method used in the transformer temperature analysis (Swift et al., 2001; Swift et al., 2001). Lobo Ribeiro et al. (2008) used optical fiber sensors to monitor the hot-spot temperature of winding and oil. Wei et al. (2012) established a thermal circuit model for the oil temperature and the winding according to the modified model and calculated the oil temperature and the winding temperature. In 2017, Li (2017) analyzed the changes in oil temperature and winding temperature of the standard working oil-immersed transformer and found that the winding temperature and oil temperature are mainly affected by the current load. In 2017, Zhang (2017) studied the operation process of the transformer. It was found that the transformer will convert a small amount of electric energy into heat energy, which will cause the winding temperature to rise sharply, accelerate the insulation degradation of the transformer winding, and lead to a shortened use time of the transformer.

In previous research work, it has been found that the hot-spot position of the winding will be affected by different loads (Godina et al., 2015). However, the hot-spot location of the transformer winding is not yet accurate (Ukil et al., 2012). It is difficult to directly measure the temperature of different positions of the transformer winding in operation by installing sensors, which has become an obstacle to analyzing the law of the transformer hot-spot temperature and the hot-spot position changing with the load. This status quo has also led to the lack of effective predictive methods for the hot-spot temperature and transformer windings location (Susa et al., 2005). In this paper, the transformer winding temperature and oil temperature distribution model is established by the thermoelectric analogy method to analyze the changes of hot-spot temperature and the hot-spot position of oil-immersed transformers under different loads. This model can simulate the

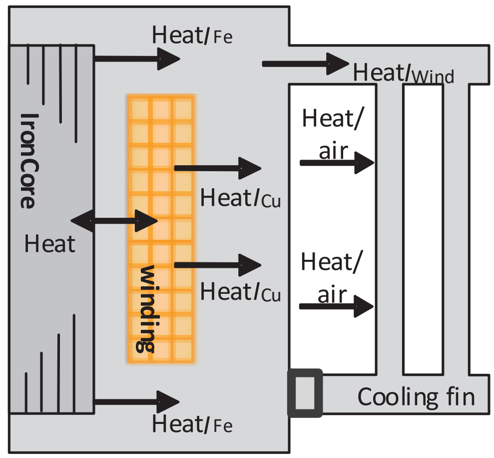

Figure 1 The transformer winding and oil heat dissipation diagram.

heat exchange phenomenon between the transformer winding and the oil. The hot-spot temperature of winding and oil is measured by sensors in the transformer temperature simulation device. Monitoring results are compared with those based on the analogy method to validate our model's reliability.

Methods

This study comprises three parts: (1) the theoretical modeling of the transformer temperature distribution, (2) the Construction of the temperature simulation device, and (3) the Temperature rise test using the transformer temperature simulation device.

1.1 Thermoelectric Analogy Method to Establish Temperature Model

Large oil-immersed transformer heating is mainly caused by load loss. The winding heat is different under different loads. The oil-immersed transformer is upright, so there is an obvious temperature gradient in the vertical direction. The heat dissipation method of the part of transformer winding and oil, as shown in Figure 1. The heat flow mainly includes the iron core heat is marked with Fe, the copper winding heat is marked with Cu, and the air cooling is marked with the wind.

The description of the physical phenomenon of the heat conductor is similar to the description of the electrical conductor. The structure of the

Table 1 Thermoelectric analog parameter correspondence

Thermal Parameters	Electrical Parameters
Heat transfer q/W	Current I/A
Temperature difference $\Delta\theta/K$	Voltage U/V
Thermal resistance $R_{th}/(K \cdot W^{-1})$	Resistance R/Ω
Heat capacity $C_{th}/(j \cdot K^{-1})$	Capacitor C/F

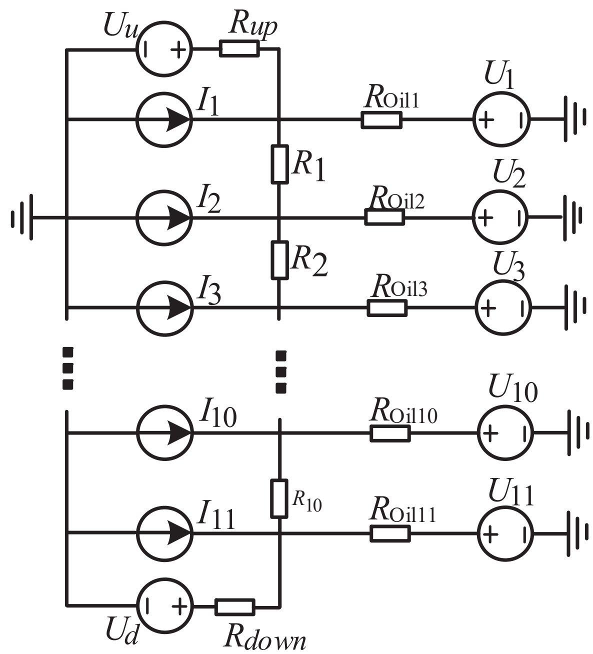

Figure 2 Thermal circuit model of the single winding temperature of the transformer.

differential equation is the same also. That is the theoretical basis of the thermoelectric analogy. The thermoelectric analogy method is used to analyze the change of the transformer winding hot-spot position with the load, find its changing law, and establish a distributed heat circuit model. The relationship between thermal parameters and electrical parameters is shown in Table 1.

The object of the model is an SFZ11-10000/35 transformer of 38.5/6.3 kV produced by a transformer company in Yunnan. Its single winding has a total of 55 series of windings, and the entire winding is divided into 11 units for research and analysis. The simplified oil-immersed transformer single-winding thermal circuit model is shown in Figure 2. In the model, $I_1 \sim I_{11}$

represent the heat flow of the winding from 1st to 11th unit winding from top to bottom; U_{up} and U_{down} represent the top oil temperature and bottom oil temperature; U_1 to U_{11} represent the oil temperature corresponding to the longitudinal position of the $1 \sim 11$ winding units; R represents the thermal resistance of transformer oil with a thickness of 2.5 mm between two winding units; R_{up} and R_{down} represent the thermal resistance coefficient of winding heat dissipation upward and downward; $R_{oil1} \sim R_{oil11}$ represent the thermal resistance of each winding unit to the transformer oil.

This model is used to study the influence of the hot-spot position of the winding with the load change during steady-state operation, so the influence of heat capacity on the temperature change rate can be ignored. The heat output per unit time of each winding unit is:

$$q = I^2R = \frac{I^2pl}{S} \tag{1}$$

Where $I(A)$ is the current through the winding, $\rho(\Omega \cdot m)$ is the resistivity of the winding, $l(m)$ is the total length of each winding unit, $S(m^2)$ is the winding cross-sectional area.

The heat of the transformer winding is mainly taken away by the transformer oil, and the rate of heat dissipation is determined by the thermal resistance of the transformer oil. The thermal resistance calculation formula is:

$$R_{th-wnd} = 1/(h_{hs}A) \tag{2}$$

where $A(m^2)$ is the equivalent convection heat dissipation area, $h_{hs}(m^2 \cdot k)$ is the convection heat transfer coefficient. The calculation formula of h_{hs} is:

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

Where $L(m)$ is the surface size that is used to dissipate the heat through the oil convection, $g(9.8\ m/s^2)$ is the acceleration of gravity, $k(m{\cdot}K)$ is the oil thermal conductivity, $\rho(kg/m^3)$ is the transformer oil density, $\alpha(K^{-1})$ is the thermal expansion coefficient of oil, $c_{oil}\,[KJ/(kg \cdot K)]\,)$ is the specific heat capacity of oil, $\mu_{hs}(kg/s^{-1} \cdot m^{-1})$ is the viscosity of the oil when the internal temperature is stable, $\Delta\theta_{hs}(°C)$ is the temperature difference between the winding and the surrounding transformer oil.

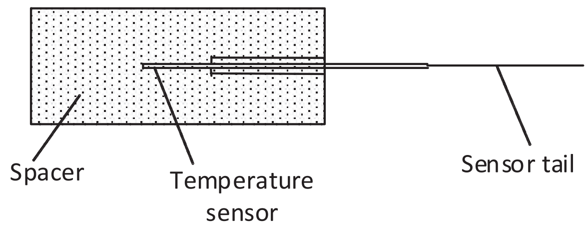

Figure 3 Schematic diagram of the thermocouple Installed.

1.2 Transformer Simulation Device Construction

The experiment is to conduct a temperature rise test on the transformer simulation device, and to monitor the winding temperature and oil temperature in crucial positions of the device in real-time. In order to dissipate the heat generated by the windings into the oil, gaskets are used between the windings of the transformer simulation device (the thickness of the resin gasket is 2.5 mm). When the sensor is installed, make an opening slightly larger than the sensor size (1 mm diameter) in the gasket, and the diameter of the opening is 1.2 mm. When it reaches a certain depth, drill a small hole with a depth of 6 mm and a diameter of 1 mm, and install the thermocouple in the gasket, as shown in Figure 3.

The oil temperature and winding temperature monitoring system of the transformer simulation device is shown in Figure 4. A total of 15 thermocouple sensors are arranged. There are 11 winding units in the simulation device, and a gasket with a thermocouple is installed between each winding unit, and the winding temperature of each unit is detected in real-time. The 11 winding units are distributed evenly, and thermocouples are placed at the bottom of each winding unit. In order to monitor the oil temperature, bakelite and bakelite strips are installed on the upper and lower ends of the iron core and near the windings. Two thermocouple temperature sensors are tied to the bakelite to measure the bottom oil temperature and the top oil temperature respectively. Three sensors are tied to the bakelite strip and measure the oil temperature at 20%, 48%, and 76% of the winding height respectively.

The photo of the thermocouple sensor installed in the transformer simulation device is shown in Figure 5.

Use aviation terminals to lead the thermocouple signal from the transformer device box, and connect 15 electrical signals from the aviation terminal to the inspection instrument. The inspection instrument analyzes and demodulates the electrical signals, converts them into temperature parameters, and uploads them to the computer. By monitoring different position

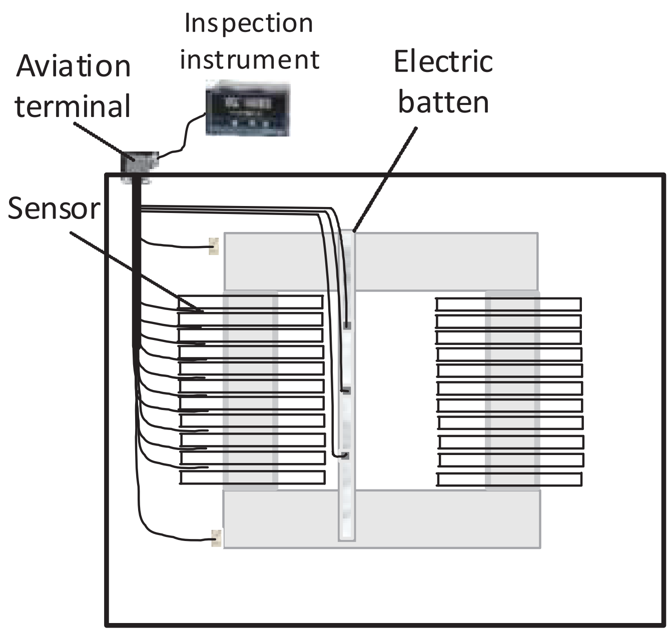

Figure 4 Schematic diagram of the installation and layout of the sensors.

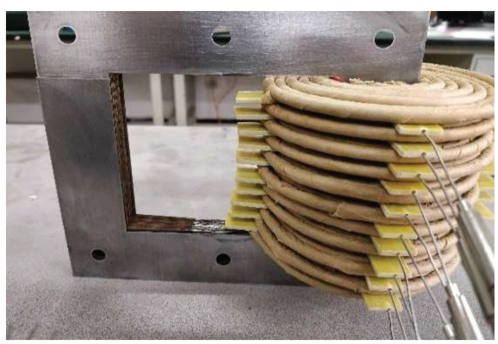

Figure 5 The photo of winding thermocouple installation.

sensors of thermocouples, the internal winding and oil temperature of the transformer simulation device can be monitored in real-time.

1.3 Transformer Simulation Device Experiment

The total winding resistance of the simulated device developed is 158 Ω. When the winding voltage is adjusted to 190 V, 216.5 V, 230 V, and 250

V with a voltage regulator, the temperature data measured by the simulation device are obtained. These data measured by the simulation device are compared with the temperature data measured by the SFZ11-10000/35 transformer at rated power, 1.3 times rated power, 1.48 times rated power, and 1.73 times rated power. The data obtained by the two methods are relatively close, and the maximum temperature difference is only 1.17°C, which can meet the requirements of the experiment.

Apply current to the simulated windings for the temperature rise test. Use a voltage regulator to adjust the voltage to 190 V, 216.5 V, 230 V, and 250 V and connect to the windings. The winding coils are at 1.20 A, 1.37 A, 1.46 A, and 1.58 A current operation, which can simulate the SFZ11-10000/35 large oil-immersed transformer windings running at rated power, 1.3 times rated power, 1.48 times rated power, and 1.73 times rated power. During the testing, the winding temperature is stable after 8.2 hours with a current of 1.20 A under the ambient temperature of 20°C, the values of the 7th and 8th temperature sensors from bottom to the top still change, but the maximum fluctuation is only 0.1°C. After 8.9 hours of 1.37 A current, the winding temperature is stable, and the values of temperature sensors of the 6th, 7th and 8th from bottom to the top still changed, but the maximum fluctuation was only 0.1°C. The 1.46 A current of the windings passed 10.2 hours, the temperature of the winding is stable, and the values of the 6th and 7th temperature sensors from the bottom to the top still change, and the maximum fluctuation is only 0.2°C. The winding temperature is stable after 11.5 hours after 1.58 A current is applied to the winding, and the 6th and 7th temperature sensors' values still change, but the maximum fluctuation is only 0.3°C.

Results

The temperature data of transformer simulation device winding and oil under different current are shown in Tables 2 and 3.

Based on the top oil temperature and bottom oil temperature measured by the simulation device, the boundary conditions U_u and U_d of the transformer winding temperature model can be calculated. The oil temperature at 0%, 20%, 48%, 76%, and 100% of the winding height in the experimental device is shown in Figure 6. Fit the oil temperature curve of the experimental device, the oil temperature corresponding to the height of each winding unit can be obtained according to the fitting result, namely $U_1 \sim U_{11}$.

Table 2 Analog device winding temperature data at different currents

Ratio of Measured Points to Winding Height (%)	Temperature at Different Currents(°C)			
	1.20A	1.37A	1.46A	1.58A
0	70.6	76.1	82.6	86.3
20	76.2	81.4	87.1	91.3
40	79.8	85.9	90.9	95.6
50	82.7	87.9	92.8	97.1
60	84.9	89.6	93.9	98.3
70	86.9	91.2	94.8	98.9
80	88.2	91.7	94.5	98.1
90	87.5	90.9	93.7	97.8
100	87	90.5	93.4	96.3

Table 3 Analog device oil temperature data at different currents

Ratio of Measured Points to Oil Height (%)	Temperature at Different Currents(°C)			
	1.20A	1.37A	1.46A	1.58A
0	57.3	61.5	65.2	68.1
20	61	65.2	70.6	73.6
48	68.2	72.3	76	79.8
76	75.3	78.1	81.3	84.9
100	81.5	83.8	86.3	88.7

Under different loads, the simulation results of the analog electrical method of the transformer thermal winding are shown in Figure 7. According to the simulation results of different powers in Figure 7, when the thermal circuit model works at rated power, the hot-spot position of the simulation result is 85.88% of the winding height, and the hot-spot temperature is 88.51°C. When the thermal circuit model works at 1.3 times the rated power, the hot-spot position of the simulation result is 79.85% of the winding height, and the hot-spot temperature is 91.24°C. When the thermal circuit model works at 1.48 times the rated power, the hot-spot position of the simulation result is 75.63% of the winding height, and the hot-spot temperature is 94.96°C. When the thermal circuit model works at 1.73 times the rated power, the hot-spot position of the simulation result is 70.8% of the winding height, and the hot-spot temperature is 99.04°C. It can be obtained from the model simulation

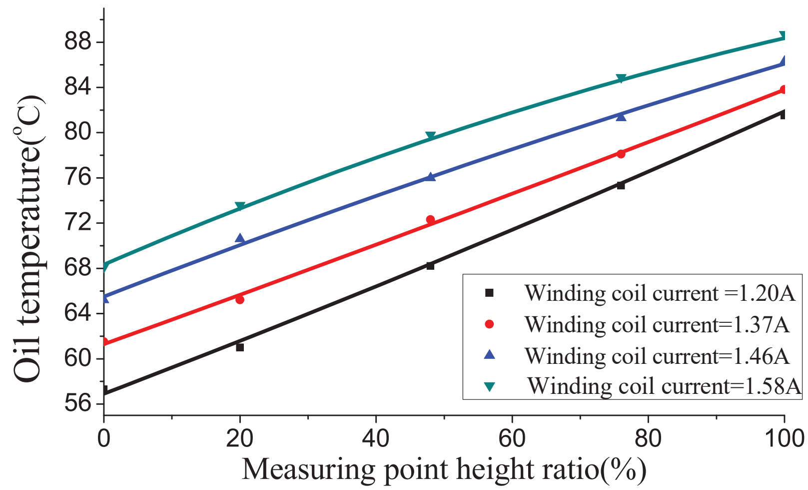

Figure 6 Oil temperature diagram under different loads.

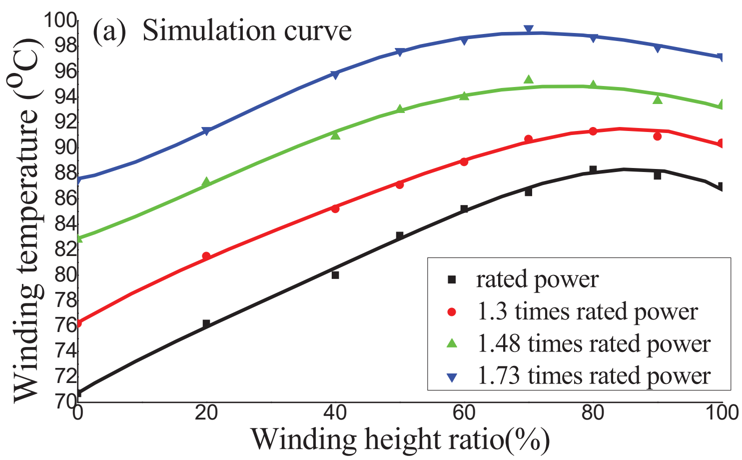

Figure 7 Diagram for simulated results under different powers.

that the transformer winding hot-spots appear between 70.8% and 85.88% of the winding height.

The fitting curve of the measured temperature of each winding point of the transformer simulation device under different currents is shown in Figure 8. According to the experimental results of different powers, when the transformer simulation device works at 1.20 A, the hot-spot is 87.48% of the winding height, and the hot-spot temperature is 88.27°C. When the

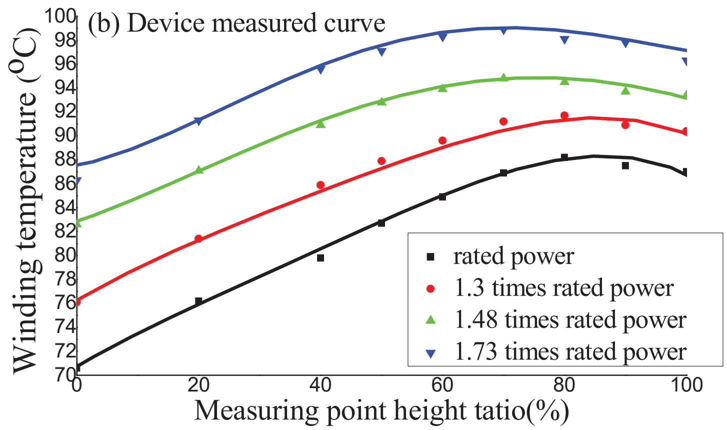

Figure 8 Diagram for Transformer Simulation Device measured curve under different current.

Table 4 Hot-spot data of Thermoelectric analog method model simulation results and simulation device measurement results

Rated Power	Simulation Results		Device Measured Results	
Multiple (Times)	Hot-Spot Height Ratio(%)	Hot-Spot Temperature (°C)	Hot-Spot Height Ratio (%)	Hot-Spot Temperature (°C)
Rated	85.88	88.51	87.48	88.27
1.3	79.85	91.24	81.66	91.18
1.48	75.63	94.96	75.03	94.51
1.73	70.8	99.04	70.85	98.30

transformer simulation device works at a current of 1.37 A, the hot-spot position is 81.66% of the winding height, and the hot-spot temperature is 91.18°C. When the transformer simulation device works at 1.46 A current, the hot-spot is 75.03% of the winding height, and the hot-spot temperature is 94.51°C. When the transformer simulation device works at 1.58 A current, the hot-spot is 70.85% of the winding height, and the hot-spot temperature is 98.3°C. From the simulation device's measured data, it can be concluded that the hot-spot of the transformer winding appears between 70.85% and 87.48% of the winding height.

Based on the simulation model established by the thermoelectric analogy method and measured by the experimental simulation device, the hot-spot position and temperature data of the transformer winding under different loads are shown in Table 4.

The simulation based on the analog thermoelectric method is consistent with the measured data. The maximum error of their results is only 0.74°C. The model simulation results and the transformer simulation device's measured value have similar trends in the change of winding hot-spot position when the load power increases, i.e., the winding hot-spot position is shifted downward.

Discussion

This study uses the combination of the thermoelectric analogy model and transformer winding temperature rise simulation device to overcome the difficulty that sensors cannot accurately measure the temperature of various transformer winding parts during the operation. Using the analog thermoelectric method simulation data and the actual measurement data of the simulation device, the hot-spot location and temperature change law of the transformer under different loads are studied.

The analysis of the charts and data shows that the heat dissipation in the transformer oil is due to the convection, the oil temperature gradually increases from bottom to top. The temperature of the upper part of the transformer winding is significantly higher than the lower part. According to the experimental results, the transformer winding hot-spot appears between 70.85% and 87.48% of the winding height, the heat dissipation of the transformer oil on the top of the winding, the temperature at the top of the winding decreases, the winding hot-spot temperature is located at the upper position of the winding but not the top. As the load of the transformer increases, the temperature of the winding rises, and the heat dissipation of the transformer oil convection cycle increases also. The heat generation and heat dissipation of the top winding change proportionally. The heat generated by the oil passage between the windings is greater than the heat dissipation, so the hot-spot temperature of the transformer winding will change as the load increases. The height of the position on the winding appears to decrease. At the rated power, the winding hot-spots appear at 85.88% of the winding height, and the winding hot-spots at the 1.3 times rated power, 1.48 times rated power, and 1.73 times rated power drop 5% respectively. Those findings can help for determining a proper location where the temperature sensors can be installed appropriately to achieve a more efficient detection and prediction for transformer winding temperature during the operation.

Conclusions

Based on the thermoelectric analogy method, this study established a model that can be used to study the temperature and location of the hot-spot in the transformer winding and then verified the simulation results with the transformer simulation device. The results show that the hot-spots are located between 70.80% and 85.88% of the winding height, whereas the hot-spot is calculated of a position at 85.88% of the winding height under the rate power. The hot-spot position of the winding moves down by 5% in turn at 1.3, 1.48, and 1.73 times the rate power respectively. The hot-spot temperature at rated power, 1.3 times rated power, 1.48 times rated power, and 1.73 times rated power is 88.51°C, 92.1°C, 94.96°C, 99.04°C, respectively. In this study, a feasible method to analyze the relationship between hot-spot location and load is proposed. It also provides practical information for predicting the hot-spot temperature of the transformer and selecting position selection of the temperature sensor installation.

Acknowledgments

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Biographies

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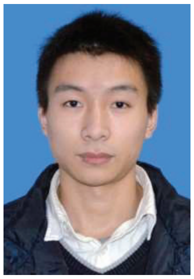

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