Research on hot spot temperature monitoring technology of transformer winding

Danping Jia1*, Liying Huangfu2

School of Information Science and Engineering, Shenyang University of Technology, Shenyang, Liaoning, 110870, China
*Corresponding author’s email: jiadp@sut.edu.cn

Abstract. A temperature monitoring system based on fiber grating is designed to realize real-time measurement of the hot spot temperature of transformer windings. This paper introduces the principle of fiber grating temperature measurement, and use the Maxwell and Fluent modules in ANSYS to simulate and analyze the electromagnetic field-fluid field-temperature field of the transformer to obtain specific information about hot spots so that the fiber grating can be placed reasonably. Through the fiber grating wavelength demodulation system based on volume phase grating, the center wavelength value of the grating is obtained, and the quantitative relationship between the center wavelength and temperature is found, which proves the feasibility of the system.

1. Introduction

In recent years, various industries in our country have developed rapidly, and the electric power industry has also developed rapidly. In the power system, the power transformer is one of the most important equipment in the transmission and distribution of electric energy. It has a great influence on the economy of electric energy transmission, the flexibility of distribution, and the safety of use. Therefore, the reliable and safe operation of the transformer is of great significance to the power system. In order to effectively avoid transformer damage due to excessive temperature or overheating, real-time monitoring of the transformer's hot spot temperature has also become more and more necessary [1].

At present, there are mainly two methods for calculating the hot spot temperature of a transformer, namely, indirect calculation and direct measurement. There are generally three indirect calculation methods: empirical formula method, thermoelectric analogy method and numerical calculation method. The direct measurement methods mainly include infrared temperature measurement, thermocouple temperature measurement, thermal resistance temperature measurement and optical fiber temperature measurement. Because fiber optic sensors have the characteristics of small size, light weight, high voltage resistance, electromagnetic interference resistance, timeliness and good reliability, their applications in power systems will gradually increase [2], and they are suitable for temperature measurement in transformers.

2. Fiber Bragg Grating Measurement Principle

Fiber grating is a passive components, the medium of an optical fiber core refractive index changes periodically, the wavelength of the reflected light and transmitted light are related to the grating refractive index modulation cycle and core index. The change of the temperature, strain can change the period and the refractive rate of the grating, and affecting the wavelength value of the reflected light and transmitted light [3].
FBG (fiber bragg grating) is a kind of optical fiber grating, its refractive index modulation depth and grating period are constants. When the broadband light through the FBG, the specific light will be reflected, and the rest of the light are transmitted. The principle of fiber grating temperature measurement is shown in Figure 1.

![Figure 1. Schematic diagram of fiber grating temperature measurement](image)

According to the coupled mode theory of optical fiber, the center wavelength of FBG reflected light is \( \lambda_B \), which satisfies the condition:

\[
\lambda_B = 2n_{\text{eff}} T \tag{1}
\]

Wherein: \( n_{\text{eff}} \) is the effective refractive index of the grating, \( T \) is the grating period, \( \lambda_B \) is determined by \( T \) and \( n_{\text{eff}} \). With the temperature, strain changes, \( T \) and \( n_{\text{eff}} \) will also changes. so we can change the center wavelength caused by temperature and strain changes \(^4\). If the differential is carried out, the center wavelength shift of FBG is obtained:

\[
\Delta\lambda_B = 2Tn_{\text{eff}} + 2n_{\text{eff}} \Delta T \tag{2}
\]

Wherein: \( \Delta\lambda_B \) is the variation of the wavelength, \( \Delta n_{\text{eff}} \) is the variation of the effective refractive index, \( \Delta T \) is the variation of the period. As can be seen from the above equation, as long as real-time monitoring the change of the FBG center wavelength, we can get the ambient temperature of the fiber grating \(^5\).

3. Simulation analysis of transformer electromagnetic-fluid-temperature field

This paper takes 25000kVA /110kV oil-immersed transformer as the calculation object to conduct a three-dimensional electromagnetic-fluid-temperature field coupling analysis to calculate the internal temperature distribution of the transformer. The main structural parameters of the transformer are shown in Table 1. The structural model of the transformer is shown in Figure 2.

| Table 1. Transformer structure parameters |
|------------------------------------------|
| Voltage level (kV) | Current (A) | 131/374/1312 |
|---------------------|-------------|---------------|
| Core diameter (mm)  | 560         | 1360          |
| Upper yoke width (mm) | 640       | 640           |
| Fuel tank length (mm) | 5300      | 1900          |
| Fuel tank height (mm) | 3200      | 1160          |
| Low voltage winding inner diameter (mm) | 586       | 689           |
| Medium voltage winding inner diameter (mm) | 743       | 837           |
| High voltage winding inner diameter (mm) | 912       | 1061          |


3.1 Calculation of three-dimensional magnetic field of transformer

This article uses Maxwell in ANSYS to calculate and analyze the electromagnetic field of the transformer. Maxwell contains analysis modules such as electric field, static magnetic field, and transient field. The characteristics of the transformer under different working conditions can be simulated.

| Structure    | Resistivity/(Ω·m) | Relative permeability |
|--------------|-------------------|----------------------|
| Iron core    | --                | B-H curve            |
| Winding      | $1.73 \times 10^{-8}$ | 1                    |

3.1.1 Analysis of core loss

The magnetic field on the iron core is generated by the excitation current and has little to do with the change of the load. Therefore, when setting the load, a sinusoidal no-load current is applied to the low-voltage winding, the high-voltage winding and the medium-voltage winding are set to open, and the low-voltage winding. The current amplitude on each phase is the same, and the phase difference is $120^\circ$. The loss distribution on the core is shown in Figure 3.

The loss distribution on the iron core is relatively uniform. The largest part of the iron core loss appears at the intersection of the iron core column and the iron yoke. The minimum loss appears at the upper and lower ends of the iron core, and the loss strength is distributed symmetrically along the Y axis.

Figure 3. Core loss diagram  
Figure 4. Winding loss diagram
3.1.2 Analysis of winding eddy current loss

The loss of the winding is mainly caused by resistance loss and eddy current loss, and the resistance loss of the winding is related to the resistance and current of the winding. Once the load current passes through the winding, leakage flux will be generated. Therefore, eddy current loss occurs in the coil of the winding. The load is applied by current excitation, the current phase on the same-phase winding is the same, and the current phase setting difference between the different phase winding is 120°. The loss distribution on the winding is shown in Figure 4.

The losses of the transformer windings are basically symmetrically distributed along the Y-axis, and the parts with larger losses appear between the medium-voltage winding and the low-voltage winding, and the losses at both ends are relatively large.

3.2 Calculation of three-dimensional fluid-temperature field of transformer

This article uses the Fluent in ANSYS to analyze and calculate the fluid-temperature field of the transformer. When the fluid-temperature field simulation analysis of the transformer is performed, the thermal performance of the material in the transformer needs to be reset.

| structure | Density(kg/m³) | Specific heat(J/kg*K) | Thermal conductivity(W/m*K) |
|-----------|---------------|------------------------|-----------------------------|
| Winding   | 8900          | 388                    | 386                         |
| Iron core | 7650          | 466                    | 48                          |
| Tank      | 7850          | 486                    | 82                          |

Table 4. Transformer oil material parameters

| Temperature (K) | Density (kg/m³) | Specific heat (J/kg*K) | Thermal conductivity(W/m*K) | Viscosity (kg/m) |
|-----------------|-----------------|------------------------|-----------------------------|-----------------|
| 273             | 893             | 1764                   | 0.1330                      | 0.1072          |
| 303             | 876             | 1890                   | 0.1306                      | 0.0184          |
| 333             | 858             | 2015                   | 0.1283                      | 0.0060          |
| 363             | 841             | 2140                   | 0.1260                      | 0.0029          |

In the internal temperature conduction process of the transformer, the heat transfer between the tank wall and the air is convective heat transfer, and the external environment temperature and the initial temperature of the transformer are both set to 20°C. Set the heat dissipation coefficient on the surface of the transformer tank through the parameters given by the manufacturer. The top of the tank is set to 10 W/(m²*K), the side of the tank is 15.1 W/(m²*K), and the bottom of the tank is 8.2 W/(m²*K), heat sink the heat transfer coefficient is 28.0 W/(m²*K). Use the core and winding losses calculated by Maxwell simulation as the heat source.

The calculation of the transformer fluid field also needs to set the initial conditions, and set the initial speed of the transformer oil to 0 m/s. The circulation of transformer oil is affected by gravitational acceleration and oil properties. Set the overall gravitational acceleration to 9.81 m/s², and the direction is the negative direction of the Y axis. The simulation results are shown in Figure 5 and Figure 6.
As can be seen from the simulation results, when the ambient temperature is 20°C, the hot spot temperature calculated by the transformer simulation is 81.12°C. On the same horizontal line, the temperature on the winding is the highest, followed by the iron core, and the temperature in the transformer oil is the lowest. This is because the windings and core are used as heat sources, and their heat dissipation conditions are worse than those of the transformer oil outside, so the temperature on the windings and core is higher than the temperature of the transformer oil. And the temperature of the medium voltage winding of the transformer on the same horizontal line is the highest, followed by the medium voltage winding and finally the high voltage winding. This is due to the combined effect of loss and heat dissipation conditions. Through the analysis of transformer performance parameters, it can be known that the loss of the high-voltage winding is the lowest, and the loss of the medium-voltage winding is between the high-voltage winding and the low-voltage winding. In addition, the medium-voltage and low-voltage windings are located at the heat source high-voltage. Between the winding and the iron core, there are narrow oil passages on both sides, and the windings dissipate heat by convection and heat dissipation with the oil in the oil passage, and the heat dissipation conditions are relatively poor. And for the medium voltage winding, it is surrounded by the main heat source high voltage winding and low voltage winding, the middle oil channel is narrow, and the heat dissipation condition is relatively worse, so the hottest temperature appears on the medium voltage winding.

4. Design of system temperature measurement scheme

The experimental platform of this system is mainly composed of three parts: optical temperature measurement module, demodulation system and host computer display unit. Among them, the optical temperature measurement module is composed of a broadband light source, a coupler and a fiber grating. The function of this part is mainly to provide a light source for the FBG, while reflecting the optical signal conforming to the Bragg wavelength to the demodulation system; the demodulation system mainly includes the FBGA solution Modulation module, this module converts the reflected light signal into an electrical signal, and at the same time transmits the information from the USB to the computer. The upper computer display module completes the communication with the hardware system, and the measured value is collected and displayed in the upper computer interface in real time.

![Figure 7. The principle of the system diagram](image)
The system wavelength demodulation module will use the fiber grating wavelength demodulation module produced by BaySpce in the United States. This module can detect the C-band (1525-1565nm), L-band (1565-1605nm) or the specified wavelength range, and the measurement spectrum range is relatively short. Wide, and can detect multi-channel spectra at the same time, higher wavelength resolution (±20pm), faster response speed (<0.6ms). Utilizing its fast response and accurate demodulation spectrum, it is widely used in the field of fiber grating sensing [6].

The display module of the host computer is realized by LABVIEW program, and the collection, processing and display of spectrum data and wavelength information are realized by calling DLL function by using LABVIEW program. According to the formula of wavelength and temperature, the temperature display function is successfully realized on the front panel. At the same time, the wavelength-power waveform diagram is established, which can display the data information more intuitively. The threshold temperature is also designed. When the monitoring temperature exceeds the threshold temperature. The warning light will turn on to achieve the alarm function.

5. Whole machine experiment and data analysis

The device was selected according to the needs of the experiment, and the experiment platform was built according to the temperature measurement system of fiber grating. The physical connection diagram of the system is shown in Figure 8.

![Figure 8. Fiber Bragg grating temperature measurement system in kind connection diagram](image)

| Temperature/℃ | First measurement /nm | Second measurement /nm | The third measurement /nm | Fourth measurement /nm |
|---------------|-----------------------|------------------------|--------------------------|------------------------|
| 20            | 1550.064              | 1550.072               | 1550.065                 | 1550.064               |
| 30            | 1550.158              | 1550.162               | 1550.170                 | 1550.159               |
| 40            | 1550.271              | 1550.264               | 1550.265                 | 1550.275               |
| 50            | 1550.349              | 1550.367               | 1550.363                 | 1550.353               |
| 60            | 1550.453              | 1550.473               | 1550.467                 | 1550.465               |
| 70            | 1550.564              | 1550.586               | 1550.573                 | 1550.536               |
| 80            | 1550.663              | 1550.661               | 1550.654                 | 1550.642               |
| 90            | 1550.781              | 1550.762               | 1550.766                 | 1550.756               |
| 100           | 1550.861              | 1550.864               | 1550.859                 | 1550.865               |

According to Table 5, the temperature value and the wavelength value are fitted by the least square method, and the curve diagram of the relationship between temperature and wavelength is established as shown in Figure 9.
Figure 9. Graph of temperature and wavelength

It can be seen from the Figure 10 that the temperature has a good linear relationship with the central wavelength of the fiber grating. The above data is fitted by the cftool function in MATLAB, and the expressions of the two are obtained as:

$$\lambda = 0.0097T + 1550$$

$$R^2 = 0.9989$$

(3)

$\lambda$ is the central wavelength value of the optical fiber sensor, and $T$ is the temperature value. From formula (3), it can be seen that the measurement sensitivity of the fiber Bragg grating is 0.0097 nm/℃, and the fitting rate is 0.9989, indicating that it has good linearity. At the same time, this formula is brought into the peak-finding wavelength algorithm, and the temperature value can be displayed in the upper computer interface.

6. Conclusion

The hot spot temperature monitoring system of transformer winding based on fiber grating designed in this paper can realize temperature monitoring. The electromagnetic-fluid-temperature field of the transformer is simulated, and the approximate distribution of the transformer winding hot spots is obtained, which provides a theoretical basis for the reasonable placement of the fiber grating. This paper sets up an experimental platform, uses LABVIEW to write a data acquisition program, acquires data from the wavelength demodulation module, and obtains the function relationship between wavelength and temperature, completes the demodulation of the FBG center wavelength, and proves the feasibility of the system.

Acknowledgments

This work is supported by Liaoning Provincial Department of Education Service Local Project (LFGD2019006). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

References

[1] Li X Q, Hou S Z, Su G B. Distributed optical fiber temperature measurement system in power system[J]. Electric power science and engineering, 2008, 24 (8): 37-40.

[2] Liu Yuan, Zhao Lin, Wang Jiqiang, Hou Moyu, Li Zhen. Optimal design of fiber grating temperature sensor for transformer winding[J]. Shandong Science, 2017, 30 (02): 55-60.

[3] Liu Y H. Fiber bragg grating sensor technology and application of [J]. sensor in the world, 2005 (3): 20-23.

[4] Jin Y X, Liu T, Fang T. Experimental research on fiber bragg grating temperature sensor based on[J]. Labview Journal of lasers, 2009, 30 (1): 32-33.

[5] Hou Dan, Wei Guangyuan, Qian Zheng, Zheng Min. Application research of fiber grating sensor in monitoring the hot spot temperature of transformer winding[J]. Electrical Measurement and Instrumentation, 2014, 51 (21): 47-51.

[6] Wang Li, Yang Honglei, Qin Weiqi, Liao Tianming, Song Qipeng, Ma Guoming. Distributed temperature monitoring method of distribution transformer based on fiber Bragg grating[J]. Guangdong Electric Power, 2019, 32 (01): 152-157.