OIL-IMMERSED TRANSFORMER ONLINE HOT SPOT TEMPERATURE MONITORING AND ACCURATE LIFE LOSE CALCULATION BASED ON FIBER BRAGG GRATING SENSOR TECHNOLOGY

Xin ZHANG
Shenzhen Power Supply Co. Ltd.– China
51938176@qq.com

Ronghui HUANG
Shenzhen Power Supply Co. Ltd.– China
13631561618@139.com

Weizhao HUANG
Shenzhen Power Supply Co. Ltd.– China
Goodbean2000@163.com

Shenjing YAO
Shenzhen Power Supply Co. Ltd.– China
yaosenjing@139.com

Dan HOU
T&S Communications Co., Ltd.– China
houdan@china-tscom.com

Min ZHENG
T&S Communications Co., Ltd.– China
zhengmin@china-tscom.com

ABSTRACT

The insulation capacity of electric power transformer will be affected by running in overheated conditions, and the winding hot spot temperature is the main limiting factor of transformer load, so the winding hot spot temperature should be measured accurately. Online temperature monitoring method using Fiber Bragg grating is presented in this paper. By the application of optical fiber grating temperature sensor in oil-immersed transformer, electromagnetic interference is avoided and direct temperature measurement of internal transformer can be realized. The system is built in an 110kV oil-immersed transformer and the transformer is put in operation for 10 months, it works safely and the measurement temperature data is stable and accurate. Based on the data, an accurate estimate of transformer life loss is work out through continuous integration of hot spot temperature and measurement time.

Keywords: *oil-immersed transformer; fiber optic Bragg grating; temperature measurement; service life evaluation; hot spot temperature measurement*

1 INTRODUCTION

Oil immersed transformers play an important role in the power transmission system, and directly related to the power grid safety, efficiency and economic operation. It is important to evaluate the transformer health state and service life.

If transformer working in overheated conditions, the insulation ability of transformer will be decrease [1-2]. The transformer insulation operation life generally follows the six degree rule: the annual average temperature should be 98℃ with normal life, when the temperature more than or less than 98℃, that increase or decrease of every 6℃, the life of the transformer will reduce half or increase double[3].

Winding hot spot temperature is the main limiting factor of transformer service life, and it should be accurately measured [4-5].

To get the transformer hot spot temperature, there are mainly two ways: direct and indirect measurement methods.

The indirect method of transformer hot spot temperature always realized by thermal simulation measurement or indirect calculation estimation[6], by this way there is a great impact, because its parameters will be influenced by nominal parameter and oil conduit design, it is hard to get the accurate temperature. The French power grid has been out of this method now[7].

The direct internal temperature measurement of transformer can be by the way of electrical signal, infrared signal, and optical signal. The traditional measurement methods adopt such as thermocouple, thermal resistance and other ways are susceptible to electromagnetic interference, and limited by service life; the infrared temperature measurement method is mainly used for inspection, its operation is convenient, but it is very difficult to be used for online detection. The traditional methods are also susceptible to background noise and electromagnetic interference.

The optical fiber temperature measurement methods are mainly based on fiber Raman scattering, Brillouin scattering, fluorescence temperature [8], semiconductor [9] and the optical fiber bragg grating temperature [10-11]. Optical fiber shows very excellent insulating performance, transmission of sensitive measuring element and the signal is composed of light, and thus it will not be affected by the electromagnetic interference. Raman scattering and Brillouin scattering measurement is subject to the installation of the optical fiber distribution and spatial resolution, it is difficult to make accurate temperature [12-13]; fluorescence temperature measurement and semiconductor thermometer using absorption technology, it is limited by one single fiber can connect only one sensor, it is difficult to realize multi-point monitoring; and it also will be influence by the intensity of the fluorescence.

The applications of optical fiber grating temperature measurement inside the transformer are rarely reported at present. One application of fiber grating sensor embedded in the winding process was finished by China electric power research institute, the requirements of manufacture and construction is strict and high[14].The FBG monitoring scheme is introduced in this paper, fiber grating sensor and its installation can be realized inside the transformer when repairing or manufacturing. For the FBG sensing case we finished, the transformer is working stable and the measurement data is accurate. It provides a new technical means for the internal temperature measurement of oil-immersed transformer.

2 THEORY OF FBG SENSING

FBG is manufactured by laser irradiation through phase mask. Its working principle is shown in Fig. 1, when a broad-wind laser light spread along the fiber, it will reflected, and the narrow band optical fiber grating reflected back to the specific wavelength, the central wavelength of FBG can be get by spectrum analysis.

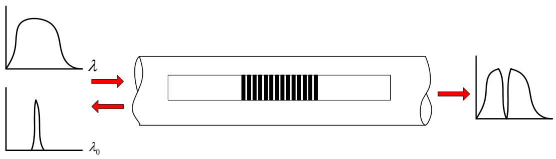

Fig.1 FBG sensing theory

The central wavelength of FBG will varies with temperature, and it is a temperature measuring element with excellent performance. The central wavelength of optical fiber grating can be measured and the temperature can be analyzed through the fixed relationship between temperature and wavelength.

The central wavelength of light reflected by FBG can be described as equation below:

$$\lambda = 2n\Lambda \qquad (1)$$

λ is the wavelength of reflected light, n is the effective index of refraction, Λ is period of FBG. n and Λ will be influenced by temperature, for temperature sensors, the relative wavelength variation is

$$\Delta\lambda / \lambda = (\alpha + \zeta)\Delta\theta \qquad (2)$$

In formula (2), α is thermal expansion coefficient of optical fiber, the change of FBG period mainly caused by it; ζ is thermal optical coefficient, which relate to the changes of the refractive index of the fiber, $\Delta\theta$ is temperature variation, $\Delta\lambda$ is wavelength variation.

Define $\alpha_T = \lambda(\alpha + \zeta)$ as the sensitivity coefficient of FBG temperature sensing, the relationship between wavelength variation and temperature variation can be described when only temperature changes. In this paper, FBG temperature coefficient is 10pm/℃, and the linear coefficient can reach 0.9999.

The light continue to transmit along the fiber, when pass the fibre brag gratings, it will be reflected one by one, through measuring the wavelength of reflected light, multi points temperature sensing can be realized by serial connect way of fibre brag grating series.

3 ONLINE TEMPERATURE MEASUREMENT SYSTEM

The scheme of online fiber optic temperature detecting system is shown as Fig. 2.

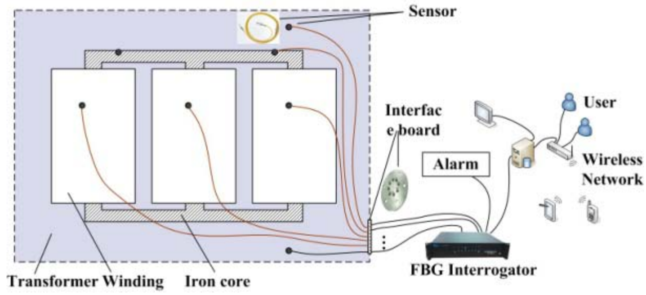

Fig. 2 Temperature online monitoring system scheme

FBG temperature sensors are installed in top oil level, iron core, windings, bottom oil level according to need, and the fiber is exported through an interface board, and the signals be connected to FBG interrogator. The system adopts fiber as the only transmission medium, the electromagnetic interference and insulation performance of transformer influence can be avoided. The following is a detailed description of each part.

FBG temperature sensors: its measuring range is from -20℃ to 300℃, and it will not be influenced by electromagnetic interference, it can compatible with transformer oil, it can also tolerate such as kerosene vapour phase drying, hot oil circulation transformer manufacturing process. It can be easily mounted to the transformer winding, iron core, busbars, electrical contacts and other regional hot spots.

Optical interface board: it is produced with patented technology, made of stainless steel, it could be installed in the transformer tank wall and ensure that there is no leakage from the transformer and optical signal can achieve outside with low loss.

Fiber grating sensing interrogator: the online temperature measurement host, there are multiple fiber channels and relays, the device also can drive alarm device; at the same time, the monitoring data can be stored in database files, and can be queried and exported conveniently; there also has open data transmission interface in the host. ModBUS and IEC61850 protocol is built in the interrogator and the data can be transmitted to server, be viewed through the online terminal, it also allow users to connect on remote way, and can be access to query data from wireless terminal equipment.

4 APPLICATIONS ON TRANSFORMER

In this application, FBG sensors are installed in 110kV oil immersed transformer during its return to factory repairing period, the measurement position lies in high-voltage windings, top oil, bottom oil, busbars and iron core. There are 2 sensors installed on every A/B/C phase high voltage windings, which position is between the second and the third winding cake, respectively, in the position between the fourth and the fifth line cake of winding; There is one sensor installed on bottom oil level, and 2 sensors on top oil level, 2 sensors on iron core and 3 sensors on busbars: a total of 14 sensor.

The sensors installed on iron core and winding are placed in blocks and the blocks are fixed between iron cores and winding cakes; sensors installed on other place are fixed by cloth binding. The installation is shown as Fig.3- Fig.4.

Fig. 3 sensor installed on iron core

Fig. 4 sensor installed on winding

5 RESULTS AND ANALYSIS

5.1 Temperature Rising Experiment

A Pt100 oil temperature gauge was installed to compare with the FBG temperature sensor during temperature rising experiment and the result is shown as Fig. 5.

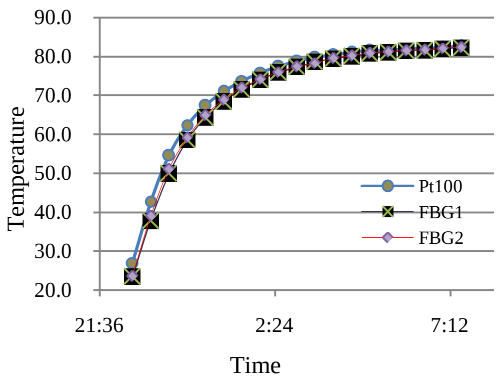

Fig. 5 Two methods of top oil temperature measurement results

From Fig. 5, when the oil temperature come to be stable in the end, the measurement value of Pt100 oil temperature gauge and FBG sensors are very close (the oil gauge is 82.7℃, the FBG sensors are 82.2℃ and 82.3℃, difference of them is no more than 1℃). It also can be proved that the FBG sensors are accurate and stable from trend of the temperature.

The temperature distribution in transformer is shown in Fig. 6 through temperature rising experiment.

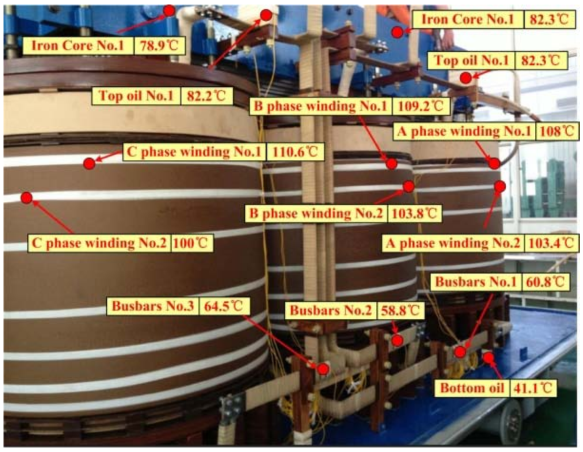

Fig. 6 temperature distribution in transformer

According to IEC 60076-2, the hot spot lies on the highest temperature measured between windings, so we can get the hot spot in temperature rising experiment lies in C phase high voltage winding, between cake 2 and cake 3.

5.2 Thermal Life Loss Calculation

Thermal aging rate defined in GB 1094.7 is shown as formula (3):

$$V = 2^{(\theta - 98)/6} \qquad (3)$$

And thermal life loss of transformer L is calculated as:

$$L = \sum_{n=1}^{N} V_n \times t_n \qquad (4)$$

In formula (4), V_n is thermal aging rate, and t_n is time interval, n is index of time interval, and N is total number of time interval.

Thermal life loss can be calculated via hot spot temperature from the steps below:

1) Calculate thermal aging rate of A/B/C phase high voltage winding.

2) Calculate thermal life loss with thermal aging rate.

3) Calculate the accumulation of time interval and get the max value as thermal life loss of transformer.

Thermal life loss of transformer in temperature rising experiment is shown as table 1,

Tab. 1 thermal life loss of transformer in temperature rising experimen(Unit: hours)

work time	A phas	B phase	C phase	life loss
10.5	20.68	26.10	29.62	29.62

The maximum value of three phases is 29.62 hours and it is the thermal life loss of transformer.

The thermal life loss of transformer from July of 2013 to March of 2014 is shown as Fig. 7.

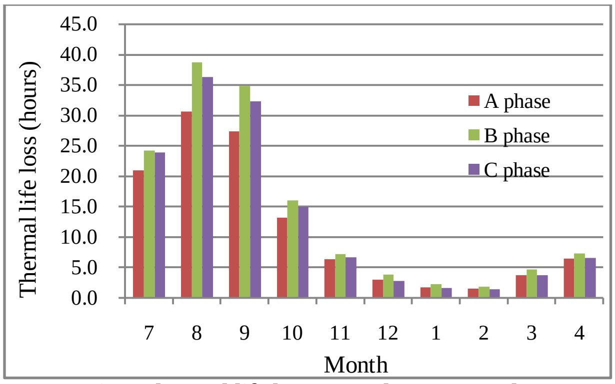

Fig. 7 thermal life loss more than 10 months

From July to October the thermal life loss of transformer is more than that in November to March of next year, and it is because of the ambient temperature and power load are higher between July to October.

Thermal aging is an important factor of transformer life loss. Estimation of thermal life loss according to online temperature monitoring results provides an important reference for transformer healthy state estimation. At the same time, the estimation can be used as an important basis for efficient and economical transformer load regulation.

6 CONCLUSIONS

An online temperature monitoring system using fiber brag grating sensors is presented in this paper. Through the installation of optical fiber grating temperature sensor in oil-immersed transformer, electromagnetic interference is avoided and direct temperature measurement of internal transformer can be realized. The system works safety and the measurement temperature data is stable and accurate. Based on the data, an accurate estimation of transformer life loss is completed through continuous integration of winding temperature and measurement time, and this estimation provides an important reference for transformer healthy state estimation and economical transformer load regulation.

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BIOGRAPHY

Zhang Xin (1984-), male, Bachelor, master candidate, engineer. His research field focus on power transmission and transformation equipment state monitoring, data analysis and supervision. His email: 51938176@qq.com