Real-time Temperature Monitoring System Using FBG Sensors on an Oil-immersed Power Transformer

ZHANG Xin¹, HUANG Ronghui¹, HUANG Weizhao¹, YAO Shenjing¹, HOU Dan², ZHENG Min²

¹. Shenzhen Power Supply Co. Ltd., Shenzhen 518000, China; ². Shenzhen T & S Communication Co. Ltd., Shenzhen 518000, China

Abstract: Over-heating issues will affect the safe operation and life-time of an oil-immersed transformer; therefore, it is necessary to monitor the temperature of the windings and oil during a transformer’s operation. Fiber Bragg Grating (FBG) temperature sensors are installed to measure the temperature of windings, cores, and busbars, as well as oil temperature at the top and bottom. An online-monitoring system is used to collect and analyze temperature data over time. Analysis shows that, by using the fiber optic Bragg grating temperature sensors, the internal temperature of an oil-immersed transformer is accurately monitored in real-time. Additionally, the result can be used as good evidence to evaluate the service life and operational state of a transformer.

Key words: oil-immersed transformer; Fiber Bragg Grating temperature sensor; temperature measurement; healthy evaluation; service life evaluation; winding temperature measurement

0 Introduction

Oil immersed transformers play an important role in the power grid, which directly determines its safe, efficient, and economical operation. Therefore, it is very practical to evaluate the operation state and service life of a transformer.

Heat is generated by winding current during transformer operation, and dissipated by oil. The insulating capability will be affected when over-heated[1-2]. The transformer insulator life time is generally considered to follow the $6^\circ$C-rule: operation at the annual average temperature should be $98^\circ$C nominally, but when the temperature more than or less than $98^\circ$C, every increase or decrease of $6^\circ$C causes the life of the transformer to reduce by half or increase double, respectively[3].

Winding hot-spot temperature is the major limiting factor of transformer load, and needs to be accurately measured[4]. As stated in the national standard[5], “because the precise location of hot-spot is not generally known beforehand, local temperature may vary from point to point, and also with time, depending on random variation of oil flow. Therefore it is advisable to utilize several sensors at the same time.”

There are two major methods to measure the winding temperature: direct and indirect methods. By the indirect method winding temperature is measured by thermal simulation, or estimated by indirect calculation[6], where measurement results are determined by temperature modelling. Since the actual transformer parameters and oil duct are often different from designed situations, the simulated result always contains a large error. The French Power grid has already stopped using this approach[7].

The direct method can be carried out by electrical signal, infrared signal, and optical signal approaches. The electrical approaches, such as thermocouple, thermal resistance, and others, are vulnerable to electromagnetic interference, and are limited by the sensor’s life time. Infrared temperature measurement method is normally used for inspection purpose, but it is not appropriate for online monitoring, and furthermore tends to be affected by background noise and electromagnetic interference. The optical fiber approaches can be based on fiber Raman scattering, Brillouin scattering, and fluorescence temperature sensing[8], semiconductor[9]
or the optical fiber grating temperature sensing [10-11]. Optical fiber has excellent insulating performance, with the sensing element and sensing signal transmission are both based on light and thus not affected by electromagnetic interference. Raman scattering and Brillouin scattering approaches are limited by the fiber sensor arrangement and spatial resolution, therefore difficult to perform accurate measurements [12-13]; fluorescence and semiconductor thermometer approaches are based on absorption, limited by the fact that only one single sensor can be implemented on a fiber, which makes it difficult to perform multi-point monitoring; furthermore, the fluorescence method tends to be affected by optical power, and fiber bending, connector loss, and cable loss combine to the measurement error.

By writing multiple FBGs (Fibre Bragg Grating) with different wavelengths, multiple sensors can be integrated on one single fiber, and using the WDM (wavelength division multiplex) technique, the temperature distribution inside a transformer can be monitored. The sensing signal processing is carried out by wavelength spectrum analysis, which is only affected by received optical power. By proper spatial arrangement of the sensors which are directly installed at the measured position, quasi-distributed temperature monitoring inside a transformer can be achieved.

So far, the applications of FBG based temperature measurement of a transformer are rarely reported in China. One application by China Electric Power Research Institute is embedding FBG sensors into a winding when it was fabricated; however, this approach has strict requirements on fabrication and site construction [14]. In this paper, a more convenient method is introduced: FBG sensors could be installed during transformer maintenance or manufacturing. Transformers installed with sensors have been put into field service, and so far are in stable and accurate operation. A new option for oil-immersed transformer internal temperature measurement is thus provided.

1 Principle of FBG Sensing

FBG is written on an optical fiber by a laser with phase masks. As shown in Fig.1, when a broad-band light travels in the fiber, a particular central wavelength would be reflected by FBG.

The central wavelength linearly shifts with temperature, which makes FBG a perfect temperature measuring element. By measuring the central wavelength, the measured temperature can be calculated using the relationship between temperature and wavelength.

$$\lambda_0 = 2n\Lambda$$

Where $\lambda_0$ is the central wavelength, $n$ is the effective refractive index, and $\Lambda$ is the grating period. $n$ and $\Lambda$ will change with temperature. As in temperature sensor applications, the relative change in wavelength is

$$\frac{\Delta \lambda}{\lambda} = (\alpha + \zeta)\Delta \theta$$

Where $\alpha$ is the thermal expansion coefficient of the fiber, which will change the grating period; $\zeta$ is the thermal optical coefficient, which will change the refractive index; $\Delta \theta$ is the change in temperature, and $\Delta \lambda$ is the change in wavelength.

If we define $\alpha_T = \lambda (\alpha + \zeta)$ as the sensitivity coefficient of FBG, then the relationship between change in wavelength and temperature can be described when temperature is the only variable. In this paper, FBG temperature coefficient is 10 pm/℃, and linear coefficient can reach 0.9999.

The transmitted light keeps on travelling along the fiber, and different central wavelengths are reflected by different gratings. By measuring these reflected wavelengths, serial temperature sensors are achieved on one single fiber.

2 Transformer Winding Temperature Measuring System

A diagram of temperature monitoring system is
shown as Fig.2.

![Diagram of temperature monitoring system](image)

**Fig.2** Diagram of temperature monitoring system

FBG temperature sensors are installed in top oil, iron core, windings, bottom oil and wherever needed: then the fiber comes out through an interface board, and the signals are received by the FBG interrogator. Since in the system fiber is the only transmission medium, the electromagnetic interference on the signal and influence on insulation performance is avoided.

Major parts of the system are described as follows:

**FBG sensors**: measures range from $-20^\circ C$ to $300^\circ C$, not affected by electromagnetic interference, compatible with transformer oil, can stand transformer manufacturing process such as kerosene vapour drying and hot oil circulation. FBG sensors can be easily mounted to transformer winding, iron core, busbars, electrical contacts and other hot spot positions.

**Optical interface board**: patented, made of stainless steel. They can be installed in the transformer tank wall and ensure a low loss optical transmission without any oil leakage.

**FBG sensing interrogator**: the host of temperature monitoring system. The interrogator has real-time monitoring function, multiple fiber channels, and 8-circuits relays, which triggers the alarm; moreover, the monitored data is stored in database files, which provides easy access, and an open interface for data transmission is available on the interrogator. Built-in ModBUS and IEC61850 protocol enables data to be uploaded to the server and viewed at online terminals, as well as providing data access via remote connection or wireless terminal devices.

### 3 Application Case on 110 kV Oil-immersed Transformer

#### 3.1 Sensors distribution

In this case, a 110 kV oil-immersed transformer was installed with a total of 14 FBG sensors during its maintenance, to measure the temperature of windings, top oil, bottom oil, busbars and iron core. Two sensors were installed on each A/B/C phase windings, between the second and third winding disc, as well as between the fourth and fifth; one sensor was installed in bottom oil; two sensors in top oil; two sensors on iron core; three sensors on busbars.

#### 3.2 Sensors installation

The sensors installed on the iron core and windings were in the form of blocks fixed in iron core and between winding discs. Sensors for other places were fixed by cloth binding. The installation process was very easy, as shown in Fig.3- Fig.6.
4 Results and Analysis

The temperature rise test was performed after the sensors were installed. Continuous internal temperature monitoring had been performed for about 4 month until the current time.

4.1 Temperature rise test and results

The windings, iron core, busbars and oil temperature values are shown in Fig.7.

For each winding, sensor numbered #1 is installed between 2nd and 3rd winding discs, and sensor numbered #2 is installed between 4th and 5th winding discs. The environment temperature during the test was 27.3°C.

4.1.1 Impact of temperature rise on transformer service life

The highest temperature of windings was measured between the 2nd and the 3rd winding discs on the phase C winding, which was 110.6°C. According to national standard [5], this point was defined as the windings’ hot spot.

The temperature variation between copper and oil is known as 20 K. According to the hot spot temperature simulation method, with hotspot coefficient chosen as 1.3, the hot spot temperature was calculated to be 107.6°C, which equals to top oil temperature (measured 81.6°C) plus the product of hot spot coefficient and copper/oil temperature variation. The calculated hot spot temperature is 107.6−27.3=80.3 K.

In the IEC 60076-7 standard [4], the top oil temperature rise is limited to 60K, but hot spot temperature rise is not specified, while in IEC 60076-2 [17] the hot spot temperature rise is limited to 78K.

It is stated in GB/T 15164-1994, Power transformers-part 7: Loading Guide for Oil-immersed Power Transformers: ‘for transformer in accordance to GB 1094 design rules, the relative thermal aging rate is 1 if operating at 98°C hot spot temperature, and this situation is correspondent to 20°C environment temperature and 78 K hot spot temperature rise.’ According to the aging equation in GB/T 15164, due to an aging rate greater than 1, the extra life loss of the transformer after the temperature rise test (duration of 11.5 hours) is 24.7 hours. That is, performing 11.5 hours temperature-rise test will actually cost 24.7+11.5=36.2 hours from the transformer service life.

4.1.2 Windings temperature profile analysis

It can be seen from the measurement results, that the temperatures between the 2nd and 3rd windings’ discs are higher than that between the 4th and 5th. Measured temperature values at the same location are close for each winding. As stated in the national standard [5], “because the precise location of hot-spot is not generally known beforehand, local temperature may vary from point to point, and also with time, depending on random variation of oil flow. Therefore it is advisable to utilize several sensors at the same time.” In this case, only 1 sensor is installed between 2nd and 3rd winding discs. Therefore, additional sensors are necessary to discover if there is any higher temperature spot, for the purpose of higher measurement accuracy.

4.1.3 Comparison with traditional temperature gauge on top oil temperature

Traditional Pt100 oil temperature gauges are used to measure top oil temperature at two locations, which are shown in Fig.7. The temperature monitoring curves are shown in Fig. 8.

1) Temperatures measured by FBG sensors have only 0.2°C difference.

2) Temperature measured by Pt100 has a 2.3°C, where the maximum measurement value is 0.5°C higher than the FBG measured value. The temperature
measured by Pt100 gauge #2 jumped for 9.4°C during 5:00-5:30, implying that a fault may have occurred on gauge #2. Soon after the field operation gauge #2 was found broken and subsequently replaced.

4.1.4 Measurement stability analysis
As shown in Fig.9, temperature of the windings, iron core, busbars and oil rose smoothly during the temperature-rise test, indicating that the FBG sensor temperature monitoring system of oil-immersed transformer works stably and accurately in this application.

4.2 Long-term operation monitoring data analysis
4.2.1 Long-term monitoring data
A long term online monitoring was performed over 4 months, and the recorded temperatures are shown in Fig.10-Fig.16.
It can be seen from the recorded monitoring data:

1) The measured temperature shows a trend of changing with changing transformer load, indicating that the consistency of all FBG sensors is good.

2) As verified by this monitor record, the practical internal thermal profile can be described as: low at busbars and bottom oil, higher at top oil, and highest at iron core and windings.

3) The hottest temperature occurs at the B phase windings, which is 96.1 °C; however, the highest average temperature over long-term monitoring occurs at the iron core. This is because when transformer load is low, heat is mostly generated by eddy current rather than windings heat.

4) The change in temperature shows a weekly period. This is due to transformer load changing with the power consumption: lower electrical loads for consumption occur on weekends and holidays, and so transformer temperatures are lower. The peak value of temperature often occurs on Tuesday or Wednesday.

4.2.2 Relationship between measured temperature and winding current

Figure 17 is a transformer temperature curve during 6 days of continuous operation, showing the relationships between the temperatures measured by winding thermometer, hot spot temperatures measured by FBG sensors, and the corresponding current load. Figure 18 shows the oil temperature curve measured by oil temperature gauge and FBG sensors respectively over different current loads.

Fig.17 shows the temperatures measured by winding thermometer and FBG sensor, plotted with the winding current data.

It can be summarized from Fig.17 and Fig.18 that:

1) Temperatures measured by FBG sensors vary with the winding current, accurately following the change of load, while the temperature change on iron core shows a slight hysteresis effect.

2) The hot spot temperature of the windings changes with current, and is 0–8 K higher than the oil temperature measured by winding thermometer.

5 Conclusions

Online temperature monitoring system of transformer with FBG sensors can provide a real-time, accurate monitoring solution for a transformer’s internal components’ temperatures. As a direct contacting measurement, the result is more accurate than simulation and theoretical calculation. Long-term monitoring has been performed, and proven that the monitoring system is safe, reliable, and stable. The system can replace winding thermometers and oil thermometers, as well as manual inspection. Moreover, by monitoring the temperature, the life loss of transformer can be evaluated. This is an effective solution for on-line temperature monitoring of a transformer.

References


