Research Article

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Temperature detection technology of power equipment based on Fiber Bragg Grating

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Abstract: The temperature detection and alarm system of power equipment is supposed to be used in power accidents caused by overheating. In our experiment, we build a system to detect the temperature of electrical power equipment. According to the actual temperature fitting curve, the whole system uses the Fiber Bragg Gratings as the signal sensing and transmission media, using the tunable Fabry-Perot (FP) cavity filter to demodulate the fiber and a SLED light source which is considered high reliability. System control and signal processing is carried out by the STM32F407ZGT6 microcontroller and its internal single-cycle DSP. The system has the characteristics of strong anti-interference ability, high reliability and precision, simple installation, convenient maintenance, remote signal transmission.

Keywords: Fiber Bragg Grating (FBG), power equipment, temperature detection

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1 Introduction

Electricity is the lifeblood of the national economy. It is essential to ensure the safe production and stable operation of the electrical power system, harness the power of electrical equipment and improve the quality of power production, which is associated with the development and stability of the social economy. There are many equipments in the power system, such as generators, transformers, oil circuit breakers, power cables, switchgear, busbar connectors, bushing clamps etc. The temperature of devices increase because of the errors in the design of current, equipment faults, poor process quality, improper use, and bad contact conditions. According to statistics from the National Electric Power Safety Supervision and Supervision Department, many electric power accidents are caused every year due to excessive temperature or overheating of power equipment, resulting in large-scale blackouts and downtime. Therefore, real-time on-line monitoring and over-limit alarming of power equipment is one of the main methods of ensuring the safety and stability of the power system.

Because the power system environment is high voltage powered and in a strong magnetic field, on-line monitoring of the power system requires a system with strong anti-electromagnetic interference capability. The power system network is complex and there are many equipments and system monitoring points, which require multiple temperature monitoring and alarm systems. Signal conditioning circuits are generally required as traditional temperature detection elements (such as thermocouples, thermoelectric groups, thermistors, integrated temperature sensors, etc.). It is also low cost and hardly realized when the measurement points are complicated, for a long time. Monitoring systems operate with electrical signals, and their anti-interference ability is poor because of zero drift, susceptibility to corrosion and severe electromagnetic interference. Infrared temperature measurement is a non-contact measurement method. It is a technology that can be operated in a strong electric field environment. It is susceptible to environmental interference and it is difficult to install an infrared temperature probe on site. Fiber grating is a kind of sensor to detect the change of stress around and environment temperature. The fiber grating sensor has many desirable characteristics: simple structure, fine diameter, small size, light weight, anti-electromagnetic interference and strong resistance to harsh environments, high level of safety and electrical isolation, excellent op-
erability and embedding, good time domain conversion and high sensitivity; integrated sensing and transmission, long-term monitoring, distributed measurement and single-line multiplexing, convenient for wavelength division, time-division multiplexing and distributed sensing, easy to form a sensor network of point measurement etc. These advantages make up for the lack of electrical sensors and infrared sensors. Fiber grating sensors are widely used for measurement of physical quantities such as temperature, strain, pressure, and vibration in flammable, explosive, space-limited and strong electromagnetic interference environments [1]. The system applied in our experiment uses fiber gratings to achieve the temperature monitoring and alarm of electrical equipment.

2 Theory of fiber grating

In 1978, the Canadian scholar Hill et al. first discovered the photosensitivity of optical fibers in Erbium-doped silica optical fiber [2]. Since then, the research and application of fiber gratings have been opened up. Special attention has been paid by researchers at home and abroad and rapid development has been made. Fiber grating uses the photosensitivity of the fiber material to form a spatial phase grating in the core, which acts as a narrowband filter or mirror, essentially a section of fiber that changes during the core refractive index period. By applying this feature, fiber gratings can be used to make optical fiber sensors that detect variations in temperature, strain and other parameters. They have outstanding advantages in long-distance and distributed monitoring, and are widely used in aerospace, engineering, energy, chemical, shipping field etc.

There are many types of fiber gratings; they can be broadly catagorized into two groups: Fiber Bragg Grating (FBG), also known as reflection or short-period grating; the other is transmission grating, also called long-period grating. Fiber grating can be divided into periodic and non-periodic by its structure, and can also be divided into filter type grating and dispersion compensation grating by its function.

2.1 Sensing principle of Fiber Bragg Grating (FBG)

FBG is a relatively common used fiber grating sensor. It utilizes the ultraviolet photosensitivity of optical fiber materials to form a spatial phase grating within the core, which has a fixed center wavelength. After an optical signal with a certain spectrum width passed through the FBG, light with a specific wavelength is reflected along the original path, and the optical signals with other wavelengths are directly transmitted. When the FBG is changed by the external environment, its grating period changes, which causing the center reflected wavelength to be shifted. By monitoring the wavelength shift changes in the external environment can be inferred, such as temperature fluctuations or variations in strain.

When the broadband light source propagates in the FBG, only the incident light that meets the Bragg condition can be coupled into the back-propagating light wave to form the reflection spectrum of the FBG; the remaining light is transmitted to form the transmission spectrum. The broadband light source incident spectrum, FBG reflection spectrum, and FBG transmission spectrum are shown in Figures 1(a), (b), and (c), respectively.

![Figure 1: Optical FBG spectral characteristics](image)

The structure and wavelength shift of the fiber Bragg grating are shown in Figure 2. According to the coupled mode theory, the center reflection wavelength of the FBG can be expressed as:

$$\lambda_B = 2n_{\text{eff}}A$$

In the formula, $\lambda_B$ is the Bragg wavelength.

$n_{\text{eff}}$ is effective refractive index in fiber core propagation mode.

$A$ is Fiber grating pitch period.
2.2 Temperature characteristics and sensitivity of FGB

When the temperature or stress around the FBG changes, it will cause changes to the grating pitch period and the refractive index of the fiber core. In this case, the center wavelength of the fiber Bragg grating will move. According to equation (1), the FBG center wavelength shift can be expressed as:

$$\Delta \lambda_B = 2 \Delta n_{eff} \frac{\Delta \Lambda}{\Lambda} + 2 \Lambda \Delta n_{eff}$$

When at room temperature, the effective refractive index of the FBG are constant at a certain temperature range, the thermal expansion coefficient and thermo-optic effect and the thermal expansion on the effective refractive index of the grating period and mode is mainly due to change of the material scale, and the grating period. According to formula (3), the temperature sensitivity coefficient of FBG can be expressed as:

$$K_T = \frac{1}{\frac{\Delta \lambda_B}{\Lambda_B}} = \frac{1}{\frac{\alpha}{\Lambda} + \frac{\Delta \Lambda}{\Lambda} + \frac{\Delta n_{eff}}{n_{eff}}}$$

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Assumptions: The axial stress field of the FBG remains stable, and the reflected light center wavelength is only affected by the temperature field. Differentiating with respect to temperature on both sides of equation (2) yields the corresponding relationship between reflection wavelength and temperature:

$$\frac{d\lambda_B}{dT} = \frac{\alpha}{\Lambda} \frac{d\Lambda}{dT} + \frac{\Delta \Lambda}{\Lambda} \frac{d\Lambda}{dT} + \frac{\Delta n_{eff}}{n_{eff}} \frac{dn_{eff}}{dT}$$

$$\frac{\Delta \lambda_B}{\lambda_B} = (\alpha + \zeta) \times \Delta T$$

Where the temperature change, the influence of the thermo-optic effect and the thermal expansion on the effective refractive index of the grating period and mode is mainly due to change of the material scale, and the grating period. According to formula (3), the temperature sensitivity coefficient of FBG can be expressed as:

$$K_T = (\alpha + \zeta) \times \Delta T$$

The FBG temperature sensitivity reflects the relationship between wavelength relative drift $\Delta \lambda_B / \lambda_B$ and $\Delta T$. The thermal expansion coefficient and thermo-optic coefficient of FBG are constant at a certain temperature range, and the wavelength change of the reflected FBG is linear with the temperature change. When the material is determined, $K_T$ is a constant associated with the material. When at room temperature, the effective refractive index of the FBG of the quartz core is $n_{eff} = 1.4469$, the thermal expansion coefficient $\alpha$ is $0.5 \times 10^{-6} / ^\circ C$, and the thermal coefficient is $\zeta = 8.3 \times 10^{-6} / ^\circ C$ to $9.5 \times 10^{-6} / ^\circ C$. The theoretical value of the temperature sensitivity coefficient $K_T$ is approximately $8.8 \times 10^{-6} / ^\circ C$ to $10 \times 10^{-6} / ^\circ C$, while the temperature sensitivity coefficient $K_T$ of the silicon optical fiber is approximately $6.67 \times 10^{-6} / ^\circ C$.

The relationship between the center wavelength of the FBG and the temperature is:

$$\frac{\Delta \lambda_B}{\lambda_B} = (\alpha + \zeta) \times \Delta T$$

Therefore, when under the condition that the axial stress field remains stable, there is a good linear relationship between the reflection wavelength and temperature of the FGB sensor. By detecting the change of the center wavelength of the grating, the temperature value of the measured point can be calculated.

2.3 Temperature characteristics of an actual grating temperature sensor

Theoretically, the temperature change of the Bragg grating is linear with respect to wavelength. When the temperature variation is small, it is generally considered that $\alpha$ and $\zeta$ are constant. However, in practical applications, since the fiber grating has a strain characteristic, the package element and the material have a temperature-sensitive characteristic, and the thermal coefficient depends on the temperature. And since the fiber grating is naked, it needs to be packaged in practical applications. After the package progress is completed, the temperature coefficient can reach a multiple of the temperature coefficient of the bare grating.

The temperature sensitivity of the Erbium-doped single-mode fiber in the range 123 – 833K is tested. When the actual temperature range is large, the curve fitting equation is [3]:

$$\frac{\Delta \lambda_B}{\lambda_B} = 5.59 \times 10^{-6} + 5.59 \times 10^{-6} \Delta T$$

$$+ 6.17 \times 10^{-9} \Delta T^2 - 4.41 \times 10^{-12} \Delta T^3$$

Therefore, when FBG gratings are used in high and low temperature environments, it is necessary to perform non-linear corrections for temperature. When the wavelength is close to 1500 nm, the relationship between wavelength and temperature can be corrected in a non-linear manner according to equation (6).

2.4 Demodulation techniques for FBG

Accurately demodulating the displacement of the FBG wavelength due to the measured change is a key issue for the practical application of FBG sensors. Current de-
Modulation technologies include Spectrometer Demodulation, Matched Grating Demodulation, Volume Grating Dynamic Demodulation, Tunable Fabry-Perot Cavity Filtering, Spectral Encoding/Proportional Demodulation, Unbalanced Scanning Michelson Interferometers solution and Modulated Arrayed Waveguide Grating method etc [4]. Among them, the Spectrometer Demodulation method can directly read the center wavelength of the reflection spectrum and its drift, but its cost to performance ratio is low, the stability is poor, which is considered extremely uncomfortable in engineering applications. The Matching Grating Demodulation method has a relatively simple structure and high detection accuracy, but its matched gratings and sensor gratings need to be correspondingly matched, and the engineering requirements are relatively stringent. The Body Grating Dynamic Demodulation method is simple in operation and has fast response speed, however, its accuracy is influenced by many factors and it is difficult to calibrate. Spectral Encoding/Proportional Demodulation method can obtain comparatively high resolution but it is required to use the low-intensity light sources, because of this, multiplexing techniques are limited. Unbalanced Scanning Michelson Interferometer Demodulation method has a very high accuracy, however, it is easily disturbed by the surrounding environment and is not applicable to Dynamic measurement. Arrayed Waveguide Grating Demodulation has both high demodulation speed, accuracy and system spend cost. The Tunable Fabry-Perot (F-P) Cavity Filter method can directly convert the wavelength signal into an electrical signal, and has the advantages of small size, low price, high sensitivity, high utilization of light energy, simple operation, and is suitable for engineering applications. This system uses a tunable F-P filter method.

A schematic diagram of a Bragg wavelength system for demodulating a fiber grating with a tunable Fabry-Perot (F-P) cavity filter is shown on the left side of Figure 3. It consists of broadband light source, isolator, coupler, F-P filter, F-P cavity piezoelectric ceramic (PZT), photodetector and other components. The tunable FP filter uses a piezoelectric-ceramic energy-mechanical-energy conversion element to tune the cavity length of the FP cavity, and applies a periodic, stable voltage to the PZT to change the FP cavity length. In this case, the FBG wavelength can be filtered, and the wavelength of the FBG reflection spectrum is obtained [5]. During the measurement, the light from the broadband source enters the FBG temperature sensor array through the isolator and the coupler. After the FBG modulation, the reflected light with different wavelengths passes through the coupler and enters the FP filter. When the transmission position of the F-P filter completely matches the reflected light wave from the FBG temperature sensor, the maximum output power of the photodetector is obtained. At this time, the wavelength of the FBG reflected light can be calculated by reading the PZT driving voltage. In that case, the measured temperature can be obtained.

Figure 3: Principle of Tunable fiber F-P filter demodulation FBG and its Schematic of temperature detection

2.5 Light source selection

Commonly used light sources include incoherent sources such as heat light sources, gas discharge sources, light emitting diodes; coherent light sources such as solid-state lasers, liquid lasers, gas lasers, semiconductor laser diodes, fiber lasers; novel light sources such as emission lasers, photonic crystal lasers, chemical lasers, free electron lasers and integrated optoelectronic module (IOEM) etc [6]. When selecting the light source, consideration should be given to the size of the light source, input and output power, stability, coherence, spectral characteristics, degree of difficulty when coupling with the optical fiber, price and availability. A light source with a wide spectral range, large output power, and good stability is selected to facilitate the multiplexing of multiple fiber gratings and the relatively high optical power at long-distance sensing, which provides a good method for signal demodulation. This system uses a SLED light source.

3 FBG power equipment temperature detection and alarm system design experiment

Temperature sensing and alarm system for power equipment use FBG as a signal sensing and transmission
medium. Using the temperature sensitivity of FBP and the light reflection principle, it can detect the temperature change along the temperature point of the fiber grating in real time and perform over-limit sound and light alarm. An example hardware block diagram is shown in Figure 3.

The main controller adopts STM32F407ZGT6 chip. The chip is based on the latest ARM Cortex-M4 core with a maximum clock frequency of 168 MHz. It supports single-cycle DSP instructions and floating-point units, integrates control and data processing, and realizes a single-chip + DSP mode. It integrates 12-bit DAC, 12-bit DAC, USART, USB, CAN, SDIO, SPI and other serial interfaces internally to facilitate communications [7].

The on-site temperature signal is step by step collected by the fiber Bragg grating, demodulated by the F-P cavity filter, photoelectrically converted and sent to the ADC inside the STM32F407ZGT6 microcontroller to perform the data acquisition of the power equipment temperature. After single-cycle DSP data processing inside the microcontroller, the F-P cavity filter demodulation system is controlled to realize temperature display and alarm. At the same time, the system communicates with the host computer through the serial port to facilitate centralized management. The STM32F407ZGT6 microcontroller generates the sawtooth wave through the internal DAC and controls the driving voltage of the piezoelectric ceramic (PZT) of the F-P cavity filter demodulation system, thereby realizing the demodulation of the F-P cavity filter.

This system uses a SLED light source with a center wavelength of 1550 nm, an output power of 17.6 mW, and a spectral width of 78.2 nm. The sensor uses a GFRP-packaged FBG temperature sensor with a reflection bandwidth of approximately 0.2 nm, a reflectance of greater than 90% and a temperature coefficient of 19.05 pm/°C. The FBG temperature sensor was placed in the incubator and experiments were performed. The results show that the system has good linearity, and the measured wavelength and temperature are consistent with the theoretical research. The wavelength deviation of each point is within ±4 pm, and the temperature measurement accuracy of the system can be up to ±0.1°C.

4 Conclusion

The temperature detection system of power equipment based on fiber grating adopts advanced FBG as sensing unit, STM32F407 single-chip computer as control and data processing unit. It has advanced technology, realizing on-site power-free detection, intrinsically safe explosion-proof, and with measuring accuracy up to ±0.1°C. The long-term operating temperature range of the fiber grating is between −40 and 70°C, and the application range is wide. Using distributed measurement methods, the measurement points can be arbitrarily set within 5km, with multiple measurement points and flexible methods. It is small, light and low cost with anti-electromagnetic interference, lightning protection, water resistance, high temperature resistance, corrosion resistance, and good reliability. The system has a compact structure, simple installation and easy maintenance. It can be applied to remote temperature monitoring and alarming of power plants, substations, cables, and other power equipment. It can also be applied to temperature monitoring and alarming of other long-distance, harsh environment locations and equipment.

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References