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The Research of Power Cable On-line Measurement System Based on Fiber Bragg Grating Sensor

Jiyue Shi

School of Automation, Wuhan University of Technology, 122 Luoshi Road,Wuhan,Hubei 430070 P.R.China
wangbo@ujs.edu.cn

This paper puts forward a power cable on-line measurement system which is based on fiber Bragg grating. Firstly the paper analyzes several solutions to cable lines temperature measurement, then the best solution to cable temperature measurement should be chosen from characters and defects of these temperature measurements. Due to the characters and merits of fiber Bragg grating such as high sensitivity, insensitive to the electromagnetic interference and lower cost than BOTDR, a cable lines temperature measurement which is based on fiber Bragg grating has been applied to engineering application. On the basis of temperature measurement principle of fiber Bragg Grating, the power cable on-line measurement system consists of FBG sensing system, FBG demodulator, multi-channels wireless acquisition and transmission terminal, and data publishing system. This measurement accuracy is relatively high, the temperature test in laboratory across cable line is analyzed, the maximum absolute error is 0.05℃; the maximum relative error is 0.2%. Moreover, a long period of time and multiple channels engineering application, the monitoring system proposed in the paper provides a feasible scheme for the on-line monitoring of underground and submarine cable. All the results shows that the fiber Bragg grating sensing system could be used for the on-line temperature monitoring on the power transmission lines and provide technical support for the smart grid, and this FBG on-line monitoring system will have a broad prospect in engineering application.

1. Introduction

With the rapid development of the national economy, nowadays development of the power system and its transmission apparatuses are a matter of great concern, both here and abroad. Fast and safety way to transmit electric power plays a vital role for development of the power system. In order to guarantee the safety of transmission apparatuses, the on-line monitoring on transmission lines could provide reliable information, such as temperature along the transmission cables, distortion degree of the cables and the dynamic cable carrying capacity. During an amount of literature about the power transmission, overheat along the transmission cables is a serious impact on the power transmission, in the cable running processes, cable line happened before electrical fault can cause cable or accessories local temperature rise, resulting in further damage insulation until the breakdown. Thus the measurement of temperature along the transmission cables will provide reliable information for decision-making by real-time monitoring the status of cables, and maximize the capacity of transmission paths (Haoi et al., 2015).

Currently, there are several temperature measuring methods of transmission cables, mainly include direct measurement, non-contact measurement and carrier measurement (Zhao et al., 2014). The direct measurement builds surface electronic thermometer into cable lines, non-contact measurement usually use the principle of the infrared temperature surveying to measure the temperature in cable lines, and the carrier measurement is based on the Brillouin frequency shift in single-mode fiber, this Brillouin frequency shift is linear to the temperature change around the sensing fiber. The characters and defects of these temperature measurements are shown in table 1.

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Table 1: Solutions of cable temperature measurement

Measurement	Best application and its character	Defects
Direct measurement	Low cost and proven technique	Strong electromagnetic interference of transmission lines due to additional power supply and low accuracy
Non-contact measurement	Simple measurement process and low cost	Strong electromagnetic interference of transmission lines due to additional power supply
Carrier measurement	High sensitivity, insensitive to the electromagnetic interference and can be used for fiber communication	Highly demand of light source, the cost of BOTDR demodulator is high and the measurement costs too much time.

Above these methods in table1, the direct measurement and non-contact measurement are the electrical measurements and are vulnerable to strong electromagnetic interference of transmission lines which will induce instability to measurement results. In addition; the electronic measure equipment also requires additional power supply. The carrier measurement which is based on Brillouin frequency shift in single-mode fiber has several merits such as small size, high sensitivity and immunity to electromagnetic interference, but it also has its defects, for instance, the BOTDR requires a highly demand of light source and its control system, and cost of the BOTDR signal demodulator is high for measurement programme, in additional, the measurement process will cost too much time because of plenty procession of signal weighted average algorithm and frequency scanning.
In recent years, fiber Bragg grating communication and optical fiber sensing applications are a matter of great concern. Fiber Bragg grating sensing technology has become the optical fiber sensing technology in the most vigorous a technology. When directly on the core, small volume, has certain wavelength, Bragg grating can reflect wavelength modulated physical quantities such as temperature, strain of characteristics, which is widely used in the optical fiber sensing. As sensor component, fiber grating also possesses other special functions (Liu et al., 2014). For example, high ability of resisting electromagnetism disturb, small size and weight, high temperature-proof, high ability of multiplex, being liable to connect with fiber, low loss, good spectrum characteristic, erosion-proof, high sensitivity, being liable to deform and so on. At present, FBG (fiber Bragg grating) as temperature sensor components has become the main stream of development and cultivation.

2. The principle of temperature detecting method based on fiber Bragg grating

2.1 Fiber Bragg Grating measurement method

A fiber Bragg grating (FBG) is a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved by creating a periodic variation in the refractive index of the fiber core, which generates a wavelength specific dielectric mirror (Chester, 2015). As shown in Figure 1, a fiber Bragg grating can therefore be used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector.

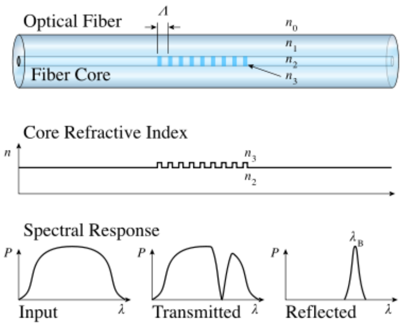


Figure 1: A fiber Bragg grating structure with refractive index profile and spectral response

As shown in figure 1, the fundamental principle behind the operation of a fiber Bragg grating is Fresnel reflection, where light traveling between media of different refractive indices may both reflect and refract at the interface. The refractive index will typically alternate over a defined length. The reflected wavelength (λ_B), called the Bragg wavelength, is defined by the relationship:

$$\lambda_B = 2n_e \ \Lambda \tag{1}$$

As shown in Eq(2), fiber Bragg grating reflection wavelength shift is influenced by temperature and stress.

$$\Delta\lambda_B / \lambda_B = (1 - p_e)\varepsilon + (\alpha + \xi)\Delta T \tag{2}$$

In Eq(2), p_e is valid elastic-optic coefficient, α is coefficient of thermal expansion, ξ is thermo-optic coefficient (dependent variable), ΔT is temperature changes. Based on these two kinds of effect, the Bragg grating can be used as sensitive element for strain and temperature measurement (Kashyap et al., 2014).

2.2 The principle of temperature detecting of the on-line measurement system

According to the basic working principle and demodulation methods of the fiber grating, the system measures the wavelength of multiple parameters FBG sensors accurately. The superiority of FBG sensor is that the sensing information is coded in the sensor wavelength. Using these measured wavelengths, we can easily calculate the stress, displacement and temperature which we want to know (Liu and Liu, 2012). According to these data changes comparison at different time, the parameter variation curve of each monitoring site is established. Among them, interface of sensors wavelength measurements as shown in Figure 2.

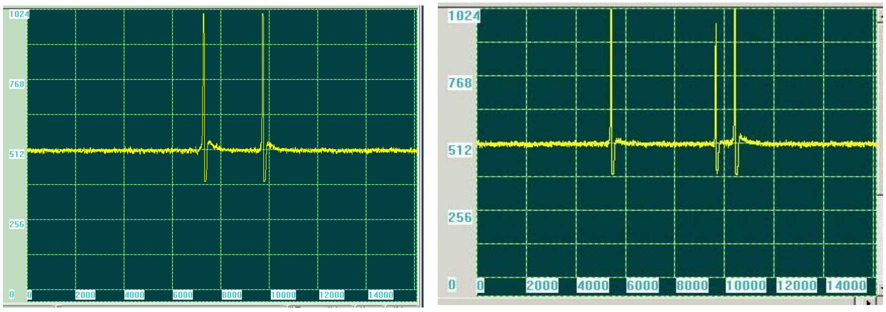


Figure 2: Wavelength comparison with measuring FBG sensors and the reference grating

The figure 2 shows that these Bragg gratings with different wavelengths have been displayed on the monitoring screen. There are two Bragg gratings in the left part of figure 2, the left peak is the wavelength of the reference Bragg grating, and the right peak is the wavelength of the measuring Bragg grating; The right part of figure 2 shows three Bragg gratings are connected in optical path, similar to the left part, the left peak is the wavelength of the reference Bragg grating, the measuring Bragg gratings are on the right side. In order to convenient identification, the minimum initial wavelength of Bragg grating is usually chosen for the reference Bragg grating.

(1) Temperature measurement: because precision of FBG sensor is very high and temperature has a great influence on it, so two FBG sensors are needed for measurement. One is used for stress measurement, the other one is used for temperature compensation.

$$T = K(\lambda - \lambda_0) + T_0 \tag{3}$$

In Eq(3), among them K is temperature coefficient, λ_1 is current value wavelength of this sensor, T is current temperature, λ_0 is the value wavelength when temperature is T_0, generally the wavelength takes T_0 = 0 ℃.

(2) Stress measurement: similar to the temperature measurement, two FBG sensors are also needed for measurement.

$$P = K[(\lambda_1 - \lambda_0) - (\lambda_{t1} - \lambda_{t0})] \tag{4}$$

In Eq(4), K is coefficient of deformation sensor, λ_1 is current value wavelength of this sensor, λ_0 is initial value wavelength of this sensor; λ_{t1} is current value wavelength of temperature compensation sensor, λ_{t0} is initial value wavelength of temperature compensation sensor.

3. Structure of the on-line measurement system and its technical parameters

3.1 System structure

The power cable on-line measurement system consists of FBG sensing system, FBG demodulator, multi-channels wireless acquisition and transmission terminal, and data publishing system. Figure 3 shows the structure chart of this monitoring system.

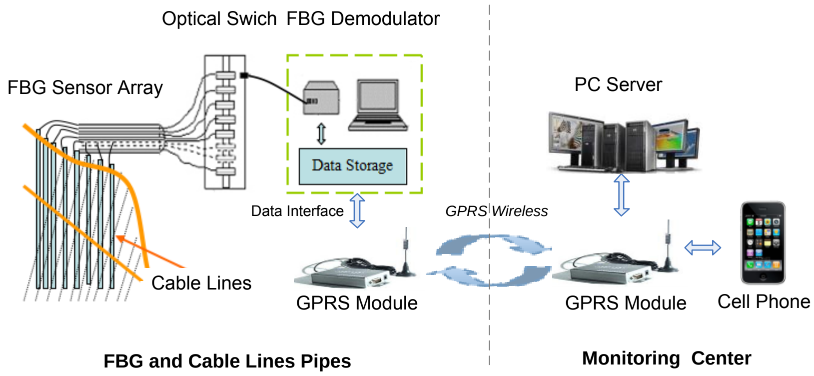
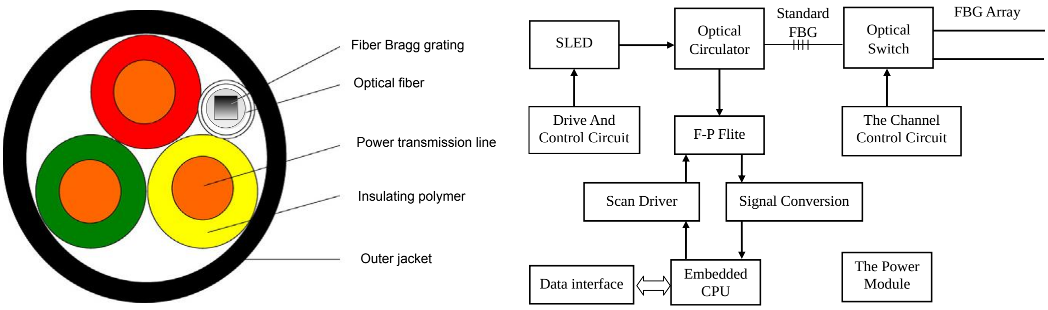


Figure 3: The configuration and structure of power cable on-line measurement system

Among them, FBG sensing system measure by laying fiber Bragg grating sensor array which is concealed in cable lines, and the sensor array consists of a set of fiber Bragg gratings which packaging in accordance with the requirements for the cable lines, and then, in tandem with single-mode fiber combined with reflection detection and F-P scanning optical filtering technology, the system realize the on-line temperature around the cable lines. The figure4 (a) shows the embedded installation of the fiber Bragg grating sensors in three phase cable.



(a) (b)

Figure 4: (a) FBG sensors cross-section of three phase cable (b) Structure of FBG sensing system

FBG sensing system is made up of broadband light source module, wavelength demodulation and analysis module, optical channel module, signal processing and data analysis module, power module and grating sensor array. Wavelength demodulation and analysis module consists of optical fiber F-P filter, scanning control circuit and photoelectric detection circuit. Optical channel module consists of optical switch and control circuit. Signal processing and data analysis module consists of A/D sampling, embedded CPU board and software module. The structure chart of FBG sensing system is shown in figure 4(b).

According to the above measuring assembly, the FBG demodulation instrument demodulates the changes of FBG sensor wavelength into the changes of temperature and stress in cable lines. The multiple channels wireless acquisition and transmission terminal gets the field data, then terminal sends data to the receiving server model by GPRS wireless. At last the data publishing system process temperature data in real-time and publishing.

3.2 Technical parameters

(1) Measurement range and precision of temperature:-20℃- +100 ℃, ±0.5℃;
(2) Measurement range and precision of stress: 0-5Mpa, 5%;
(3) Maximum measurement length of single point optical fiber: 5000m;
(4) The most single fiber measuring points: 50.

4. The performance of hybrid active power filter in power distribution system

4.1 Laboratory calibration of temperature measurement

In the system, the main work of laboratory calibration is metrological verification of temperature measurement. The testing process is directly going through test data. The measured object is connected with the measured FBG strain sensor, and the temperature measurement range is from -10℃- to 95℃. Comparing the temperature data which is detected by the system with temperature data of thermometer, then the absolute error and relative error will be calculated. In the experiment, K=99.6264℃/nm, the data is shown in table 2.

Table 2: Data of temperature test in laboratory

Standard（℃）	Measured value（℃）	Absolute error（℃）	Relative error（%）
-10	-10.02	0.02	0.2
5	5.01	0.01	0.2
20	20.02	0.02	0.1
40	39.96	0.04	0.1
60	59.98	0.02	0.03
80	79.97	0.03	0.037
100	99.95	0.05	0.05

Temperature test conclusion: the maximum absolute error is 0.05℃; the maximum relative error is 0.2%.

4.2 Engineering application

Through the laboratory test, the system is confirmed in accordance with design standards, so we put it into power cable installing application. There are the scene photos of cable lines and FBG sensors installing and burying.

Figure 5: The photos of cable lines and FBG sensors installing and burying

Through a long period of time and multiple channels measurement application, the monitoring software interface and one of temperature curves measured by FBG are shown in figure6.

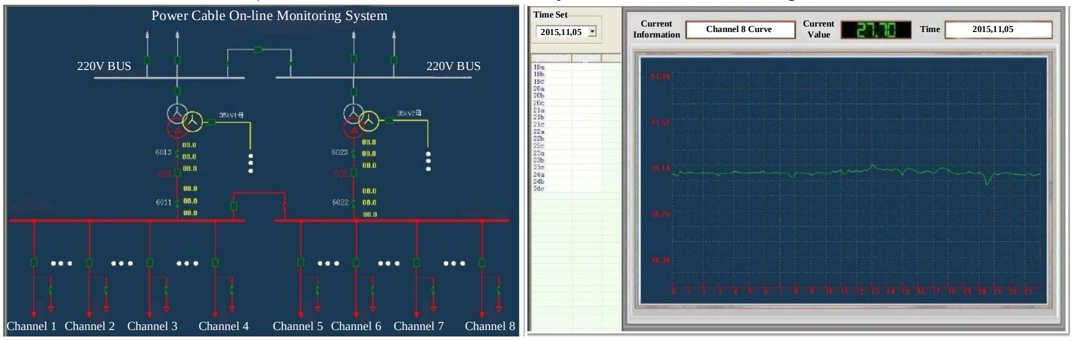


Figure 6: The figure of monitoring software interface and one of temperature curves measured by FBG

5. Conclusions

This paper puts forward a design method of on-line power cable measurement system based on fiber Bragg grating, and in order to guarantee the safety of transmission apparatuses, the on-line monitoring on transmission lines could provide reliable information, several solutions to cable lines temperature measurement are analyzed in this paper, such as direct measurement using electronic thermometer, non-contact measurement using infrared principle and carrier measurement which is based on the Brillouin frequency shift in single-mode fiber. The best solution to cable temperature measurement should be chosen from characters and defects of these temperature measurements. In addition to these monitoring measurements, fiber Bragg grating can reflect wavelength modulated physical quantities such as temperature, strain of characteristics, which is widely used in the optical fiber sensing.

Due to the characters and merits of fiber Bragg grating such as high sensitivity, insensitive to the electromagnetic interference and lower cost than BOTDR, a cable lines temperature measurement which is based on fiber Bragg grating has been applied to engineering application. On the basis of temperature measurement principle of fiber Bragg Grating, the power cable on-line measurement system consists of FBG sensing system, FBG demodulator, multi-channels wireless acquisition and transmission terminal, and data publishing system. Moreover, the temperature test in laboratory across cable line is analyzed, the maximum absolute error is 0.05℃, the maximum relative error is 0.2%, so this measurement accuracy is relatively high. Through a long period of time and multiple channels measurement application, the monitoring system proposed in the paper provides a feasible scheme for the on-line monitoring of underground and submarine cable, which can ensure the safe operation of underground and submarine cable.

All the results shows that the fiber Bragg grating sensing system could be used for the on-line temperature monitoring on the power transmission lines and provide technical support for the smart grid. The FBG monitoring system provides a new technology, method and equipment for the research of power cable monitoring and measurement, and this FBG monitoring system will have a broad prospect in engineering application.

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