



THE TRANSFORMER WINDING TEMPERATURE MONITORING SYSTEM BASED ON FIBER BRAGG GRATING

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Abstract- High temperature is one of the important reasons causing the fire in power system. Therefore, the early warning could be told by monitoring the temperature and effective measures could be taken. The corresponding accidents will be reduced. The traditional transformer winding temperature monitoring methods are electrical signal measurement and infrared measurement. Such electrical signal sensors are vulnerable to the interference of electromagnetic field, so the result of measurement is bad. Multiplexing optical path is unable to be realized by fluorescence thermometry. The optical fiber Bragg grating technology is used on temperature monitoring of transformer winding in this paper. The transformer winding temperature monitoring system based on optical fiber Bragg grating includes three parts: Temperature monitoring program based on the LabVIEW programming language, a fiber Bragg grating wavelength demodulation system and FBG temperature sensor. When the temperature of the transformer windings changes, the central wavelength of the fiber Bragg grating changes accordingly. Broadband ASE light source emits light, which is transmitted from the optical

circulator into the fiber Bragg grating. The reflected light gets into the wavelength demodulation module again through the optical circulator. Wavelength demodulation module could transmit the center wavelength of the spectral reflectance information, peak power information to the computer. The computer analyzes, processes the information and displays the data with XY graph by calling the LabVIEW program. The program can get center wavelength values at the same time then get temperature by fitting function and display temperature on the front panel of the program. The fitting line of linearity between center wavelength of optical fiber Bragg grating sensor and temperature is above 0.95. The function reveals a good linearity which fitting the wavelength changes of the optical fiber Bragg grating during this temperature range. The experimental results show that the system has high accurate measurement which meeting high precision requirements of transformer winding temperature.

Index terms: FBG, transformer winding, temperature, FBGA demodulation, LabVIEW.

I . INTRODUCTION

Power transformer is one of the most important devices in power transmission and transformation system. It is directly related for the safe, efficient and economic operation of the power grid. The temperature is the main factor affecting the insulation capability [1].It has a very important practical significance to the real-time measurement of transformer internal temperature[2,3]. At present there are mainly three methods applying to measure internal temperature of the transformer.

(1) Electrical sensor measurements. Such as thermocouple and resistance thermometer sensor, etc. These sensors are susceptible to electromagnetic interference and have limited life, so the effect measurement is not ideal[4].

(2) Infrared thermometry. This method is non-contact measurement, easily for manual operation. However it is unable to realize online real-time measurement. Additionally it is vulnerable to background noise and electromagnetic interference environment [5,6,7].

(3) Fiber optic thermometry. Distributed optical fiber temperature measurement which based on the principle of raman scattering and the principle of brillouin scattering restrains mutually among the accuracy of temperature measurement, the accuracy of spatial positioning and the

response time. It is not yet meet the requirements of accurate temperature measurement in the internal transformer [8,9,10]. Fluorescence optical fiber or the type of semiconductor transmission and reflection optical fiber temperature sensor are point temperature measurement where the point of measurement is little. It is arranged inside the transformer that tends to need based on the empirical estimation. There are certain limitations in practical application [11,12,13]. Compared with the above temperature program, the application of fiber Bragg grating (FBG) sensing technology is a good way to solve the problem of temperature measurement within transformer winding. After nearly two decades of development, FBG sensing technology is more mature. In general fiber gratings have been widely used in temperature measurement [14,15]. FBG sensors have the following advantages in the measurement of transformer winding temperature: Because of small size of sensor, it is easily buried inside the transformer and lead. Easy to utilize WDM technology cascaded multiple gratings in a single fiber. Realize quasi-distributed network measurement. Good insulation performance, immune to electromagnetic interference, suitable for high temperature and pressure in the oil and gas environment [16]. This paper based on Fiber Bragg Grating temperature measurement designs and produces transformer windings built-fiber grating sensors. It could carry out related experimental tests to achieve directly temperature measurement within the transformer winding and provide a new technical means for the internal temperature of the transformer.

II . SUMMARY OF FIBER BRAGG GRATING

Hill and his colleagues belonging to communication research center of Canada manufactured the fiber Bragg grating in 1978, which was a great development for the study and application of fiber grating has been [17]. Meltz who worked in the east Hartford united technologies research center could write fiber Bragg grating into optical fiber by selecting the wavelength of laser, or changing the Angle between the two beam of coherent light In 1988, which showed the potential value of the optical fiber Bragg grating [18]. The fiber grating written method, theoretical research and application have gained rapid development [19]. On the basis of fiber Bragg grating and long period fiber grating people has successively developed a number of fiber grating with special structure, such as chirped grating [20], phase shifted grating [21], tilted fiber grating[22],

etc. It is believed that with the need of application and further research, FBG will be more widely used in communication, sensing and other related areas in the future [23].

III. THE THEORY AND DEMODULATION TECHNOLOGY OF FBG

a. The theory of FBG

FBG is a kind of excellent narrowband reflection filter passive components. Its grating period and the refractive index modulation depth are generally constant as well as the grating and fiber axis is in the same direction. The schematic diagram is shown in figure 1.

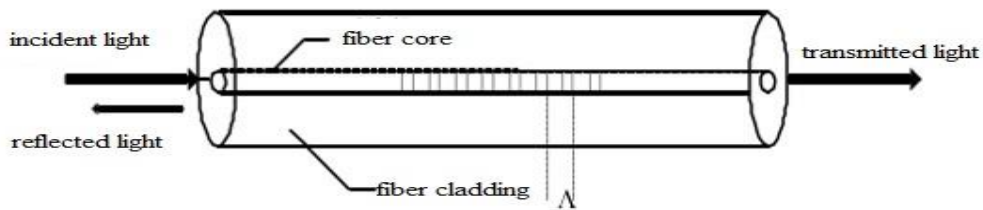


Figure1. The structure of FBG

By the structure of the fiber Bragg grating, the shape of fiber Bragg grating is the same as the optical fiber. The core of fiber has the structure which the refractive index is in the periodic change. When light waves pass the FBG satisfying the Bragg condition (the wavelength of the incident light is equal to the wavelength of the Bragg) of the light will be reflected back to form a reflection beam of light. Due to mismatch of the phase, light wave with not meeting the Bragg condition can be reflected only a weak portion, so the incident light is divided into two parts: the transmitted light and reflected light.

Based on the coupled-mode theory of optical fiber, the Bragg wavelength of FBG is shown as follows:

$$\lambda_B = 2\Lambda * n_{eff} \quad (1)$$

Wherein the parameter n_{eff} represents the effective refractive index of the fiber core, Λ is the grating period. From the above equation the λ_B of Bragg wavelength varies with n_{eff} and Λ [24,25].

When FBG sensors for temperature measurement simply the head of FBG temperature sensor can be conducted by strain-free package to overcome the effects of a certain strain realize the

temperature measurement. Due to the thermo-optic effect and thermal expansion of fiber material, temperature changes the effective refractive index n_{eff} and grating period Λ . When the center wavelength of the light reflected by the Bragg grating changes with tiny temperature occurring. You can get:

$$\Delta\lambda_B = 2 \left(\Lambda \frac{\partial n_{\text{eff}}}{\partial L} + n_{\text{eff}} \frac{\partial \Lambda}{\partial L} \right) \Delta L \quad (2)$$

Wherein, L is the length of the grating. Without considering strain bring $\frac{\partial \Lambda}{\partial L} = \frac{\Lambda}{L}$ to the above equation then we could obtain:

$$\Delta \lambda_B = 2 \left(\Lambda \frac{\partial n_{\text{eff}}}{\partial L} + n_{\text{eff}} \frac{\Lambda}{L} \right) \Delta L \quad (3)$$

$$\Delta \lambda_B = \lambda_B \left(\frac{\Delta \partial n_{\text{eff}}}{\partial n_{\text{eff}}} + \frac{\Delta L}{L} \right) = \lambda_B (\alpha + \zeta) \Delta T \quad (4)$$

By formula (4) when there is no strain effect there exists a linear relationship between the FBG wavelength $\Delta\lambda_B$ and ΔT . By measuring the FBG wavelength shift the temperature change of the FBG can be obtained [26].

b. Fiber Bragg grating signal demodulation technology

Currently the wavelength of the mobile detection scheme is put forward. Mainly in the following several detection methods: the ratio of the detection method, the M-Z interferometer detection, scanning fiber F-P interferometer method and matching grating detection method.

(1) Linear filtering proportion detection method

The principle of proportion detection method is shown in figure 2. The reflect light coming from the fiber grating through the splitting ratio of M / N coupler is divided into two. One way is sent to the detector as a reference (I_R). The other way is sent to the detector (I_F) from the linear filter. The ratio of the two signals is

$$\frac{I_F}{I_R} = A \frac{M}{N} \left(\lambda_B - \lambda_o + \frac{\Delta\lambda}{\sqrt{\pi}} \right) \quad (5)$$

The effect of light intensity and spectral fluctuation is eliminated by equation (5) and the $\Delta\lambda$ can be obtained directly. In fact the proportion of detection is to change the movement of wavelength

into light intensity through a linear filter. Changing in the slope of the linear filter, the detection sensitivity can be changed, and the linear range of detection wavelength is affected.

The detection method based on the ratio of the linear filter is relatively simple, low cost and capable of directly measuring the absolute value of the wavelength directly. It not only measures static strain but also measures dynamic strain. Its deficiency is that the measure of the resolution is not high and not suitable for multiplexed fiber grating wavelength demodulation.

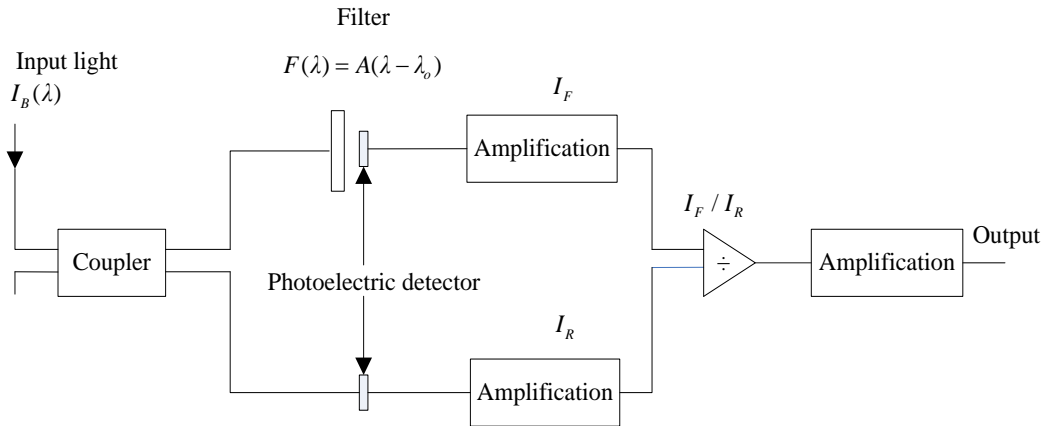


Figure2. Proportion of detection

(2) Matching fiber grating detection method

Matched fiber grating method is also called tunable optical fiber grating filter method. Choose consistent parameters of the sensing fiber Bragg grating as a matching object. Under the action of driving element the wavelength change of the sensing fiber Bragg grating is got by testing the matching fiber Bragg grating. Matched fiber grating detection mainly includes two kinds of reflective and transmission measurement methods. Measuring principle is shown in figure 3.

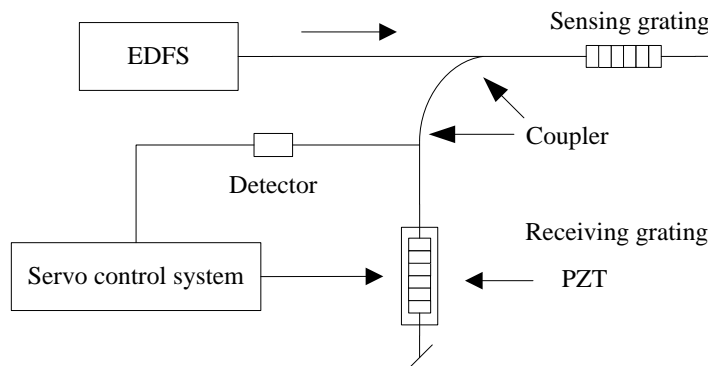


Figure3. Matched fiber grating detection method

The light emitted by a broadband light source, gets into the sensing grating sensor probe through the coupler. The reflected light gets into the matching grating through the optical coupler again. A closed control system is in this part. The piezoelectric element is tracked through the servo system, finally the wavelength of the matching FBG is consistent with the sensing grating.

This system is the reflection of matching grating detection method. The disadvantage is that the introduction of matching grating, resulting in doubling the number of grating. It would increase the light energy loss and reduce the resolution of the system.

(3) Optical fiber M-Z interference detection method

The principle of optical fiber M-Z interference detection method is shown in figure 4. Reflected light from the grating is sent into non-equilibrium fiber M-Z interferometer. The arms of the interferometer are wrapped around the piezoelectric cylinder. The outputs of low frequency signal from the detector drivers the piezoelectric cylinder to offset low frequency phase drift $\varphi(t)$. Because of the temperature produced by the reflected light wavelength drift, the optical fiber grating is equivalent to a wavelength tunable light source for M - Z interferometer. When wavelength of light changes $\Delta\lambda$, the output of phase change is like this:

$$\Delta\varphi(\lambda) = \frac{2\pi nd}{\lambda^2} \cdot \Delta\lambda = -\frac{2\pi nd}{\lambda^2} \cdot \gamma \cdot \Delta\varepsilon \quad (6)$$

The corresponding wavelength shift could be found by the output phase changes of the interferometer. The detection sensitivity is very high based on obtaining wavelength by phase change. However this kind of measurement method also has drawbacks as it is very susceptible to the surrounding environment. Environmental interference changes slowly, so it is mainly used for dynamic measurement which range is in only about 100 dB.

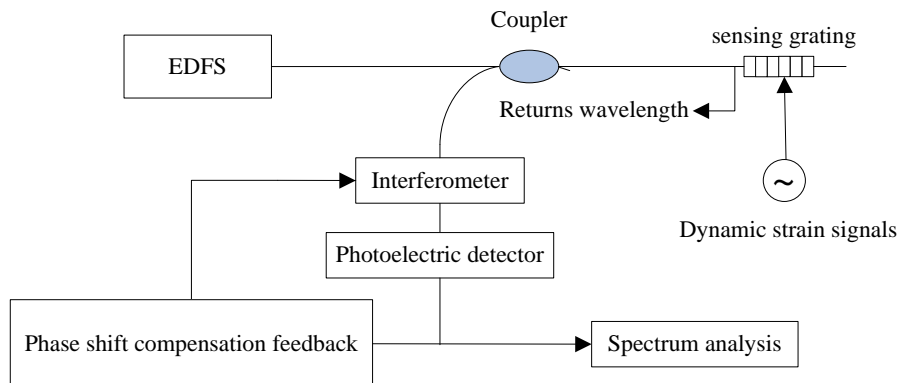


Figure4. Non-equilibrium fiber M - Z interference detection

Unbalanced fiber M-Z interferometer detection method can achieve dynamic strain resolution of $0.6n\epsilon / \sqrt{Hz}$ when the frequency is greater than 100Hz, which also could be used to achieve wavelength demodulation in the multiplexing network of fiber Bragg grating. The disadvantage of this method is that it cannot be measured absolute value of wavelength and not be used in the static strain measurement.

(4) Scanning optical fiber F - P interference detection method

Scanning optical fiber F-P interference detection method is shown in Figure 5. Reflected light of the fiber grating is fed into the tunable fiber F-P filters (FFP). The sawtooth voltage is applied to the FFP which scans near the wavelength of the fiber grating. Output zero crossings of FFP is in the peak wavelength of the fiber grating. At this time the voltage applied to FFP reflected grating wavelength. A kind of typical FFP filter is as shown in figure 6.

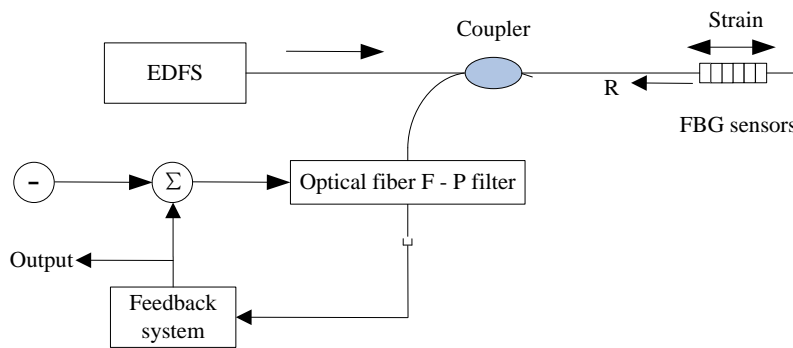


Figure5. Scanning optical fiber F - P interference detection

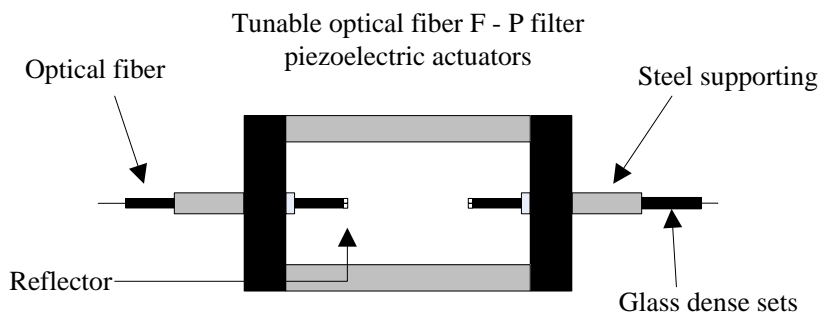


Figure6. The structure of FFP

Scanning FFP method can measure the absolute value of the wavelength. In addition it can not only measure the dynamic wavelength shift but also measure the static wavelength shift. This

method is a widely used FBG sensing signal demodulation techniques. Its shortcoming is that the price of the optical fiber F-P filter is more expensive.

Inconvenience or higher price problems exist in above several kinds of demodulation technology mentioned in the industrial field application. So the FBG Interrogation Analyzer is adopted in this article and some simple introduction is necessary to be told.

FBG Interrogation Analyzer is integrated spectral engine embracing the essential functions of optical wavelength meter, optical power meter and optical spectrum analyzer providing rapid wavelength and power measurements. From these measurements, one can quickly identify channels and derive channel wavelength shifts, channel power distribution, and other critical health monitoring information

Providing a quick and accurate measurement of wavelength and power of optical signals with a miniature device is challenging work. Desktop Optical Spectrum Analyzers (OSA) can do the job, but they are not suitable for integrating with communications systems and field inspections. The field test and system monitoring of fiber-optic communications networks requires compact size, low power consumption, high speed, high repeatability, and high reliability. FBG Interrogation Analyzer is designed to simultaneously meet these critical requirements, which uses high-resolution volume phase grating (VPG) technology and high-efficiency InGaAs array detector. The basic operating diagram for the FBG Analyzer module is schematically shown in Figure 7.

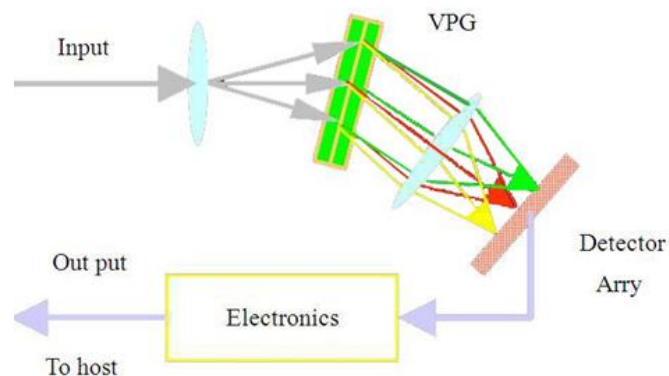


Figure7. Schematic diagram for FBG Analyzer module

The input light signal coming from a communications network or collected from the sample under test is incident on a beam-collimating lens through an optical fiber interface. The collimated beam is then directed to the spectral element (VPG), from which the different

wavelength components are separated. These angularly dispersed beams (wavelength components) are then focused onto a photodiode array by a focusing lens. Thus, the light signals at different wavelengths are measured and converted into electrical signals. The electrical outputs are subsequently transmitted to the electronic circuitry for processing and output, from which spectral information is obtained.

IV. THE STRUCTURE OF OPTICAL FIBER GRATING SENSOR SYSTEM

LabVIEW launched by National Instruments of the U.S. is a virtual instrument development platform and a high efficient graphical programming environment. At the same time wavelength detection method based on the demodulation module has advantage in high signal-to-noise ratio, simple demodulation principle, high reliability and is expected to become one of the most development potential methods of the wavelength detection[27].

Wavelength demodulation module has advantages of a small, simple read data, demodulation speed, large dynamic range, moderate accuracy, insensitive to temperature, no periodic calibration, high reliability, etc. At the same time it can obtain wavelength of the C-band to realize the measurement requirements of real-time synchronization in a complex environment. It has been widely used in the world.

The experiment platform is composed of hardware and software system to measure the temperature. Light from a broadband light source pass a circulator or coupler to reach the FBG sensors. Due to the influence of the ambient temperature, the change of related parameters in the optical fiber grating crosses into the FBG sensor demodulation devices. At the same time the demodulator transfers the data to a computer using RS232 serial port. Getting acquisition, analysis and processing of data by LabVIEW to realize the measurement of physical quantities such as strain and temperature.

The principle of FBG wavelength detection system is shown in figure 8. The light of Broadband light source gets into the fiber grating through the optical coupler. The reflected light gets into light wavelength demodulation module through the optical coupler. The demodulator transfers the information of the center of the spectral reflectance and peak power information to the computer. The computer program by calling LabVIEW program could analyze, process

information and display information on the front panel. The experimental device is shown in Figure 9.

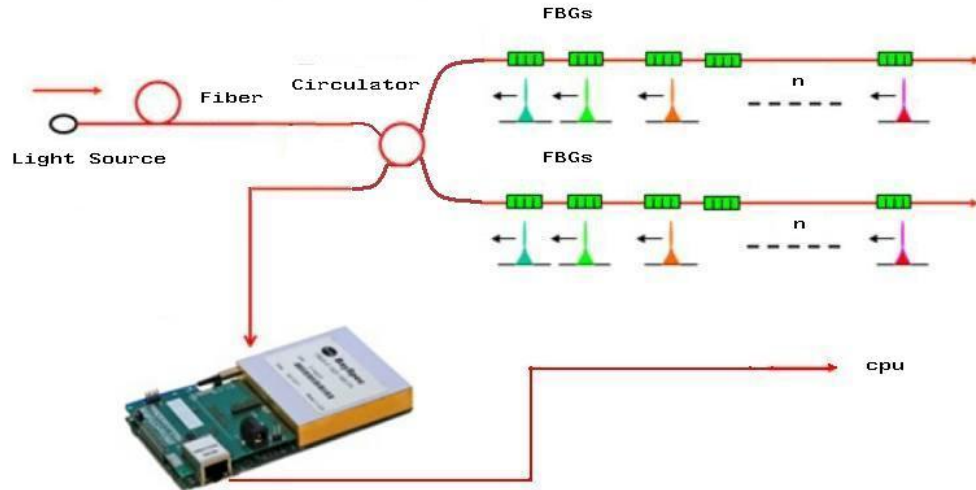


Figure 8. The diagram of fiber Bragg grating temperature sensor



Figure9. The experimental device

V. THE IMPLEMENTATION OF LABVIEW PROGRAMMING

The common programming model of LabVIEW includes standard state machine, the message queue processor, the producer/consumer design mode, the user interface event handler and the master/slave design mode, etc. This program uses standard state machine.

Standard state machine is one of the most commonly used design patterns in LabVIEW programming. Using the algorithm of the state diagram can clearly be implemented and is suitable for completing the algorithm of Moore machine scanning, namely could complete the corresponding action in the each state diagram. Standard state machine consists of a while loop, a shift register and a conditions of the structure. The shift register is used to save the current state and terminal connection of the structure of the selector state values of condition and performs the corresponding transfer code according to the state. The work of process program is shown in the following.

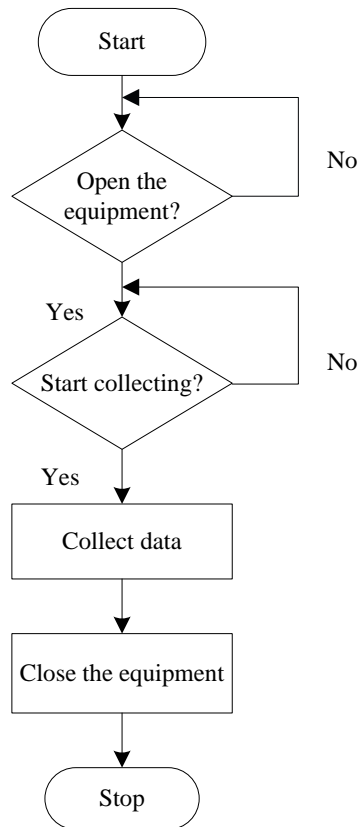


Figure10. System flow chart

Fiber Bragg grating temperature monitoring program can realize the data collection, the peak of the data, waveform display, data storage and multiplexer functions. Its main functions have the following several aspects:

(1) Data acquisition: Software contains RS232 protocol driver and the computer communicates with wavelength demodulation module by selecting the serial port. Software obtains the data by calling the dynamic link library and realizes continuous cycle collection. Demodulation module is connected to the computer via the RS232 protocol. After installing the module RS232 driver, we need to communicate with demodulation module by calling the dynamic link library functions (vose32DLL. DLL). LabVIEW call the DLL node through Calling Library functions (Call Library Function, CLF). The data acquisition process of demodulation module is as follows: module initialization->select the output parameters (wavelength) ->get wavelength array->select the output parameters (power)-> get power array.

A configuration dynamic link library function of module initialization is vosestart (int32_t nSerialType, int32 - tnPortIndex). When serial port connects to the computer through RS232,-USB line the value of communication port can be checked by device manager. If the return value is true it means success of open of equipment; If the return value is false it means failure of open of equipment. This function allocates internal memories for data acquisition. vosestop must be called to release these memories. The program block diagram of the function is shown in figure 11.

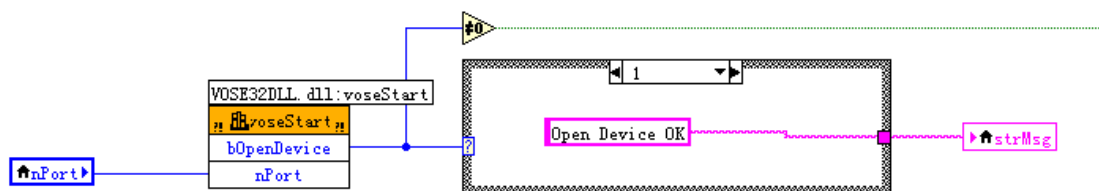


Figure11. Configuring dynamic link library function of module initialization

Select output parameter function is voseSetPixelReportMode (int32-t nPixelReportMode), and set the return value type: 0-the raw data, 1-returns to the processing of data in dBm, 2-returns the wavelength data, the function works together with the start acquiring data function. The program block diagram of the function is shown in figure 12.

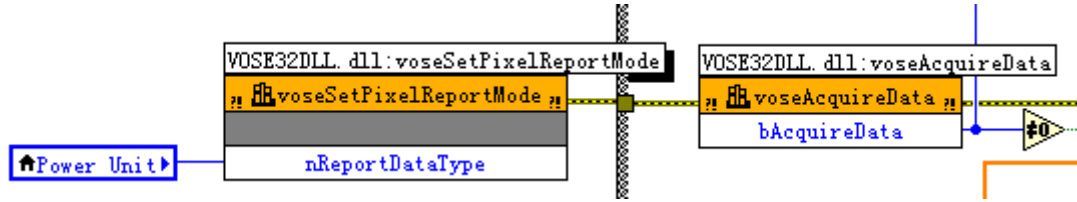


Figure12. The function of voseSetPixelReportMode

(2) Sensor fitting: The sensors numbers is written firstly. Then the data are linear fitted for each sensor. So we get fitting formula as well as the algorithm design of sensor peak searching and temperature output after fitting the sensor. The program block diagram of the function is shown in figure 13.

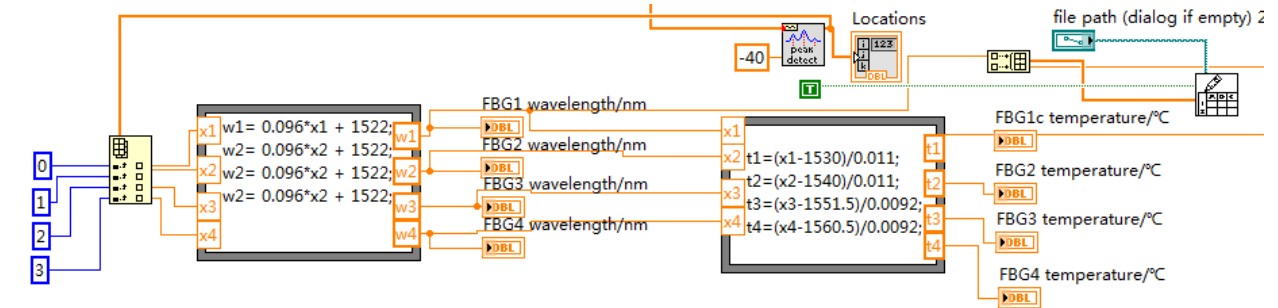


Figure13. Fitting formula and peak search function

(3) Graphic display: Including wavelength-power graphic display of sensors. A FBG sensor wavelength-power of the XY graph is as follows:

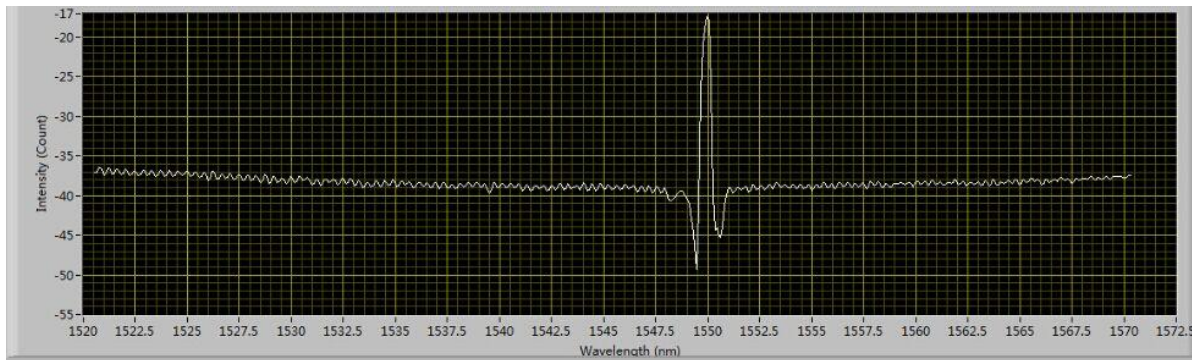


Figure14. Single FBG wavelength-power of the XY graph

You can visually display raster array spectra simultaneously in a graphical interface. The program also sets up a similar chart display interface, and is displayed as shown, controlled through a drop-down list: the left chart is the peak of wavelength of the fiber grating sensor and

the corresponding temperature, the right chart is the channel of the original spectrum. The program block diagram is shown in figure 15.

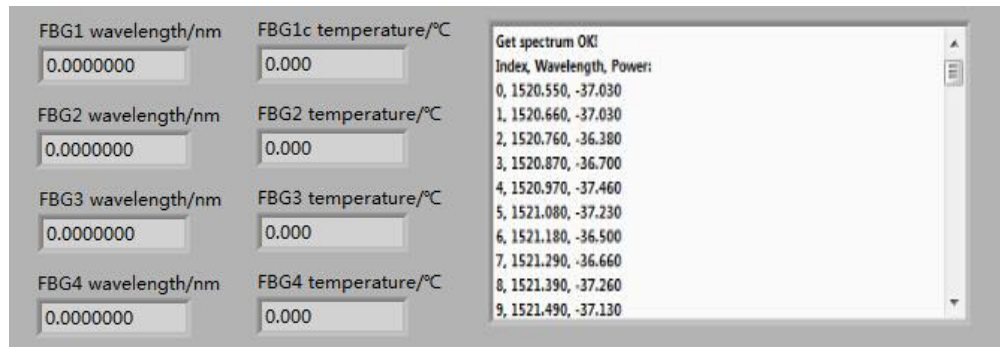


Figure15. Wavelength output display and channel original spectrum

(4) Additional features: Include peak search, temperature data storage, sensor temperature alarming and history inquiries.

"peak detection (Peak Detector)" VI in "Signal processing - signal operation" function palette of LabVIEW located each peak position and rang of the input signal sequence in FBG. A "threshold" parameter of Peak Detector VI is set to the half of the maximum value of FBG signal. "Width" parameter is set to 3. Peak Detector VI fitted of data within a period of quadratic curve in specified "width" and positioned the crest according to the fitted curve. The front panel program is shown in figure 16. The program is shown in figure 17.

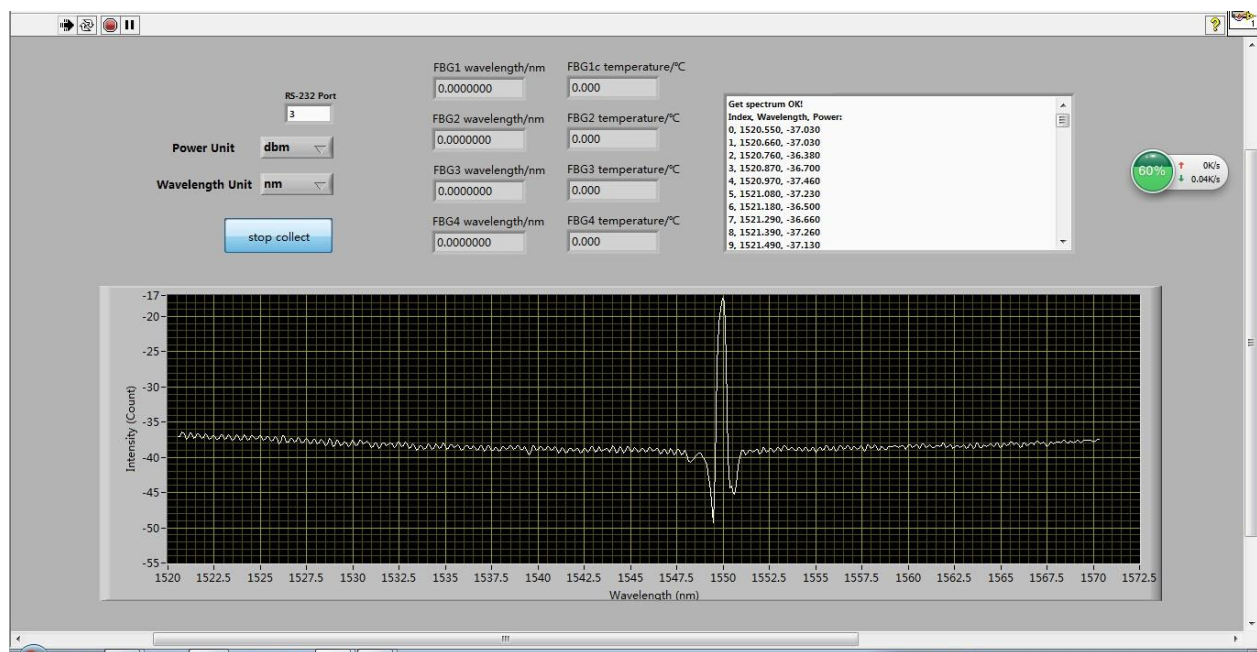


Figure16. System block diagram of the front panel

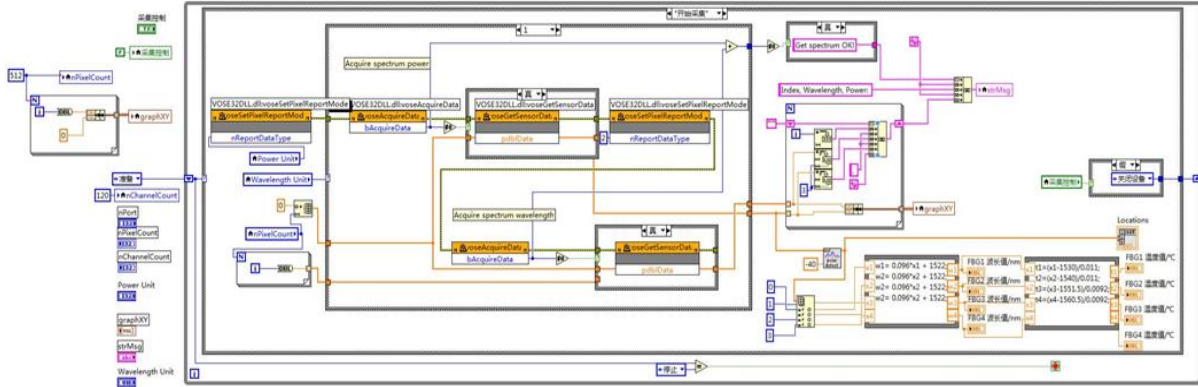


Figure17. System programming block diagram

VI. THE ANALYSIS OF EXPERIMENT RESULTS

Connect laboratory equipment according to the above light path diagram. The light signal emitted by broadband optical source. It gets into the fiber Bragg grating through the coupler. FBG sensors were placed in an incubator. The fiber Bragg grating reflected incident light according to different spectrum of wavelength. The wavelength demodulation module demodulated the reflected light signal from the FBG. The signal is transmitted to the LabVIEW collection procedure with the computer. With the change of temperature in the incubator the center wavelength of the reflected light is also changed. We can get a set of data about the wavelength signals. By tracing point method we can eventually get temperature-wavelength graph of the reflection spectrum of FBG. Measured reflection spectrum of the center wavelength of FBG would represent the outside measured physical quantities. Acquisition of the temperature and the corresponding value of the center wavelength of the experimental data shown in Table 1:

Table1. Experiment data tables of wavelength and temperature

Temperature /°C	FBG1 /nm	FBG2 /nm	FBG3 /nm	FBG4 /nm
20	1530.252	1540.255	1551.624	1561.624
30	1530.353	1540.355	1551.755	1561.755
40	1530.461	1540.455	1551.833	1561.833
50	1530.579	1540.574	1551.943	1561.943
60	1530.682	1540.686	1551.975	1561.975
70	1530.799	1540.803	1552.109	1562.109
80	1530.931	1540.928	1552.189	1562.189
90	1531.061	1541.058	1552.246	1562.246
100	1531.079	1541.083	1552.412	1562.412

The relationship between temperature and center wavelength of FBG1 is shown in figure 18.

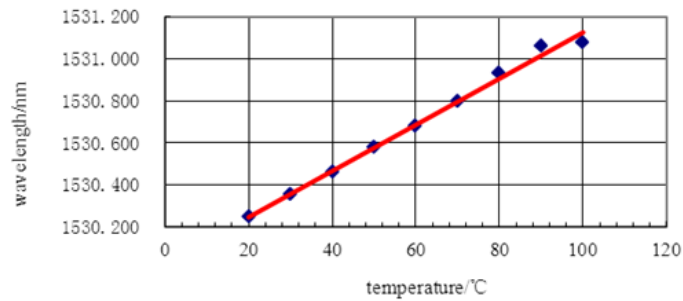


Figure18. The wavelength - temperature diagram of FBG1

As can be seen from the experimental data, the central reflection wavelength changing with temperature exhibits a good linear relationship, after linear fitting, the relation is: $y=0.011*x+1530$, $R^2=0.9933$.

The relationship between temperature and center wavelength of FBG2 is shown in figure 19. The relation is: $y=0.011*x+1540$, $R^2=0.9941$.

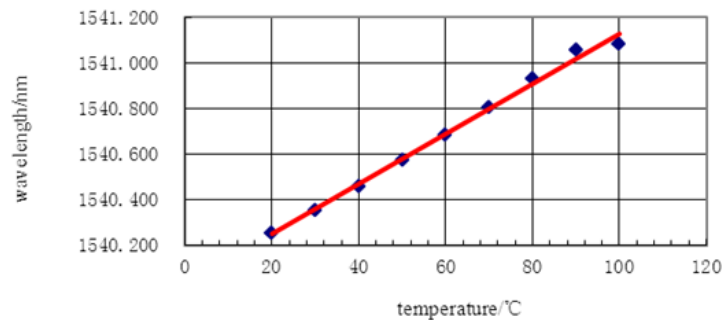


Figure19. The wavelength - temperature diagram of FBG2

The relationship between temperature and center wavelength of FBG2 is shown in figure 20. The relation is: $y=0.0092*x+1551.5$, $R^2=0.9892$.

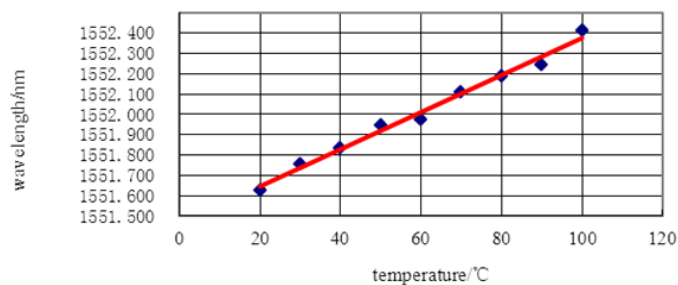


Figure20. The wavelength - temperature diagram of FBG3

The relationship between temperature and center wavelength of FBG2 is shown in figure 21. The relation is: $y=0.0092*x+1561.5$, $R^2=0.9892$.

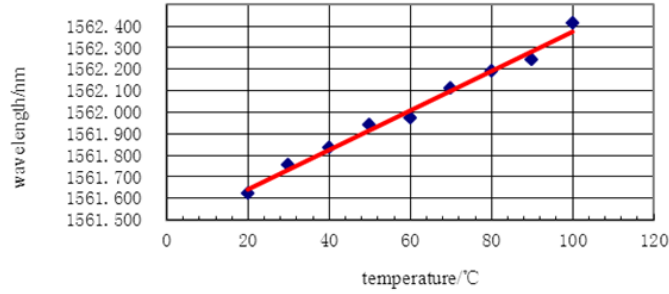


Figure21. The wavelength - temperature diagram of FBG4

The basic process of the testing error system is as follows: The fiber Bragg grating temperature sensor used in the experiment and the reference thermometer were put in the thermostat. When the temperature of the thermostat reached the prescribed temperature and became stable before test the value of the reference thermometer and temperature sensor was read. The error of the temperature sensor is the value of difference between the sensor and the reference thermometer. The reference thermometer was the thermocouple in this article. Because the thermocouple is vulnerable to internal complex electromagnetic interference within the transformer, we don't put the FBG temperature sensors and thermocouples in the transformer to calibrate.

During the test, the temperature sensor should be at least once in each test along the forward and reverse travel. Comparing the measured value of the temperature sensor and the standard thermometer, the data matched each other and the basic error was very small. We conducted the same experiment for FBG2, FBG3 and FBG4. Resulting in multiple sets of test data, the basic error didn't exceed $\pm 2^{\circ}\text{C}$. The basic error of FBG1 and FBG2 are shown in figure22.

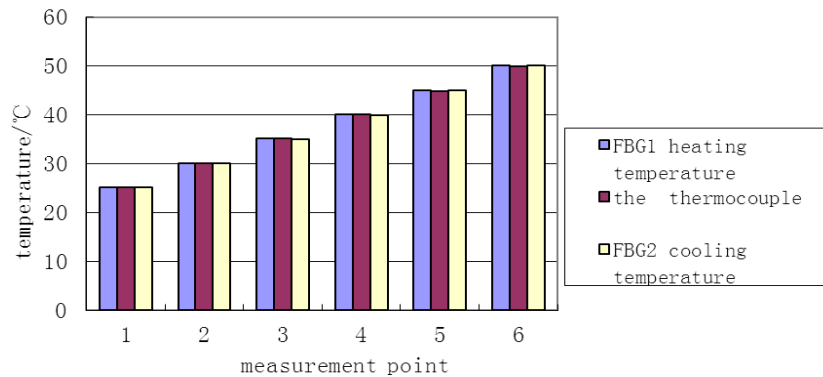


Figure22. Chart of basic error

VII. CONCLUSION

This paper introduced the concrete application of FBG sensor in domestic and foreign research status of the FBG demodulation technology. Then analyzed and compared other sensing technologies. A simple and easy to carry fiber grating temperature sensor is designed by using optical fiber Bragg grating demodulation module. In this paper the main work has the following several aspects:

(1) This paper introduced a brief analysis of the significance of transformer winding temperature measurement and several conventional temperature measurement methods. The above temperature measurement methods had disadvantages of relying on high for light source, not achieving an optical path multiplexing, post-maintenance cumbersome and higher maintenance cost. The fiber Bragg grating temperature measurement was proposed in this paper. This method had many advantages of long-term temperature measurement, corrosion resistant, anti-electromagnetic interference characteristics. It was ideally suited for the measurement of transformer winding temperature.

(2) This paper described the measurement principle of fiber grating. Further it draws the theoretical relationship between temperature and center wavelength. Then the linear scale detection method, matching fiber grating detection method, unbalanced M-Z interferometer probe and scanning fiber F-P interferometer detection method are cited. Simultaneously their advantages and disadvantages are analyzed. Wavelength demodulation module was used to conduct FBG demodulation. This method can overcome the shortage of above demodulation technology and the most obvious advantage is that it is very suitable for industrial field environment.

(3) Temperature measuring hardware platform is combined by an ASE broadband light source, optical circulator, sensing grating, wavelength demodulation module and computer, which could accurately detect the wavelength bandwidth from 1520 nm to 1560 nm.

(4) The LabVIEW software was used to design the data acquisition program, then to realize data acquisition of the wavelength demodulation module. This paper got the fitting function of the wavelength and temperature. Meanwhile, the system can realize real-time display temperature. In addition, the change of the wavelength could be obtained by calling DLL dynamic link library functions in real time. Meanwhile the corresponding temperature result was shown user interface of the program.

(5) The stability of the system was ideal and the effect was good in long time measurement.

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