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Development of Acoustic Optical Fiber Sensor for Arc Discharge in Power Transformer

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Abstract: Insulation problem is the main cause of power transformer failures and accidents. Arc discharge is an important manifestation and symptom of transformer insulation degradation. Therefore, it is of great significance to realize the online monitoring of arc discharge defects in a timely and effective manner, and to monitor the real-time status of transformers and conduct fault analysis based on them. Previous researches show that when the arc discharge generates ultrasonic signal, it will also be accompanied by a large number of audible signals. Therefore, monitoring the acoustic signal of arc discharge provides a new idea for online monitoring of transformers. In order to fill this research gap, the structure of arc discharge acoustic sensor based on fiber grating in transformer is designed. In view of the problem that the cross sensitivity of stress and temperature affects the measurement accuracy of the sensor, a double fiber grating temperature compensation method is proposed, and a transformer built-in acoustic sensor with large measurement range and excellent anti-interference performance, which has both audible sound and low-frequency ultrasound, is successfully developed. The theoretical measurement range is 1 kHz - 60 kHz. Using the built test platform for sensing the acoustic signal of arc discharge inside the transformer, the acoustic signal sensing ability of the optical fiber acoustic sensor is monitored by comparing the audible acoustic sensor and the ultrasonic sensor. The results show that the acoustic signal band is mainly 2 kHz - 10 kHz and 50 kHz - 60 kHz.

Keywords: Transformer, Arc Discharge, Optical Fiber Acoustic Sensor

1. Introduction

Power transformer is one of the core equipment in power system, which plays an important role in the safe operation of power grid. The arc discharge inside the transformer is a key characteristic index reflecting the insulation safety of the transformer. The arc discharge is mainly caused by interturn winding and interlayer windinheg faults [1]. According to the statistics of CIGRE Transformer Working Group in 2013 [2], when the arc discharge fault occurs inside the transformer, the further development of the fault cannot be stopped due to the insufficient detection sensitivity of the power system relay protection and the untimely action response, which led to the cracking of more than half of the transformer oil tanks and eventually led to an explosion accident, posing an extremely serious threat to the safe and stable operation of the power grid. The arc discharge detection method of power transformer is mainly characterized by acoustic, photoelectric and other phenomena induced by its discharge. Based on this, there are many methods for its monitoring, including optical measurement, gas chromatography, infrared thermal imaging, ultrasonic method, pulse current method and so on [3-8]. The acoustic method is one of the most commonly used methods, and the arc discharge monitoring technology based on audible sound is a relatively new monitoring and diagnosis method at present. At this stage, in view of the fact that the audible sensor of arc discharge does not generate electromagnetic signals during the acquisition and transmission of the acoustic signal of arc discharge, and has no electrical connection with the equipment, so it does not interfere with the equipment itself. The audible signal diagnosis technology is a supplement to the existing arc discharge monitoring methods, and has great research significance.

Zhao Lihua et al. selected the audible sound sensor by analyzing the characteristics of the audible sound signal in the transformer and its corresponding monitoring requirements, and finally showed that the electret capacitive audible sound sensor is suitable for the collection of audible sound signals in the transformer and has been verified by tests [9]. He et al. proposed a fiber microphone structure composed of multiple fiber bundles in 1991 [10]. With the increasing number of receiving fibers, the coupling efficiency of light will be maximized. The sensitivity of the sensing system is further improved. At the same time, due to the special structure of the fiber microphone, its anti-interference ability will be greatly improved. In 2005, Jiang Yongliang and others proposed a single fiber MFOS acoustic sensor [11]. Although the structure of the acoustic sensor has been greatly simplified, its performance is poor in response to low-frequency acoustic signals. Mohanty et al. developed a fiber grating microphone in 2006 by connecting the film and the fiber grating longitudinally, and tested it in the audible frequency range [12]. The test results showed that the microphone can detect acoustic signals of different frequencies, but it did not describe its measurement frequency band range. In 2007, Yang Jian of Tsinghua University and others developed a new type of sensing probe that can be used to sense underwater sound using fiber Bragg gratings [13]. They used two fiber gratings to form a matching grating to form a push-pull structure, which improved the sensing sensitivity of the system to underwater sound from 6 pm/MPa of bare fiber Bragg gratings to 0.36 nm/MPa. Experiments proved that the dynamic response range of the underwater acoustic sensor can reach more than 100 dB. In 2019, Yu Ruoyu et al. continuously designed and optimized the parameters of fiber Bragg grating, making fiber Bragg grating both a sensing unit and a filtering unit [14]. They designed a fiber grating hydrophone system based on an erbium-doped ring laser, and conducted experimental research on its ability to sense ultrasonic signals. Lin Huizu of the National University of Defense Science and Technology designed a hydrophone array system based on matched interference using four miniaturized fiber grating hydrophones [15]. Through experiments, they mainly analyzed the crosstalk suppression and noise reduction of the system in detail and gave some solutions. The audible sound diagnosis technology is a supplement to the existing arc discharge monitoring methods, and has great research significance.

2. Basic Principle

When the light is transmitted into the fiber, the transmission spectrum and reflection spectrum of the fiber Bragg grating will produce singularity to the wavelength of the optical signal. The basic structure of fiber Bragg grating is shown in Figure 1.

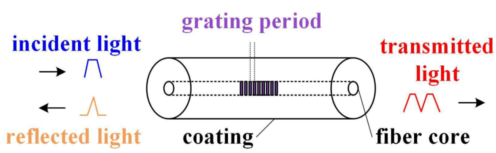


Figure 1. *Basic structure of fiber Bragg grating.*

Using the coupled mode theory of fiber grating, the equation of fiber Bragg grating can be derived as:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

which, λ_B is the central wavelength of the fiber grating, n_{eff} is the effective refractive index of the fiber, and Λ is the period of the fiber grating.

When the fiber grating is subjected to external stress, the change of the center wavelength of the grating caused by the axial stress plays a dominant role, so the acoustic signal can be simplified into an acoustic transient sine longitudinal wave model, as shown in Figure 2:

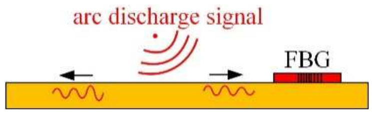


Figure 2. *Fiber Bragg grating sensor excited by longitudinal wave acoustic signal.*

Since fiber grating is more sensitive to axial stress, assuming that acoustic signal only propagates along the axis of grating, then the transmitted acoustic signal $\varepsilon(t)$ is expressed as:

$$\varepsilon(t) = \varepsilon_m \cos\left(\frac{2\pi}{\lambda_s} z - \omega_s t\right) \tag{2}$$

which, ε_m is the amplitude of the strain, λ_s is the wavelength of the acoustic signal, and ω_s is the angular frequency of the acoustic signal.

Under the dual effects of geometric effect and elastic optical effect, the shift of the central wavelength of the fiber grating reflection spectrum could be described as follows.

$$\Delta\lambda_B = \lambda_B \varepsilon_m \left\{1 - \left(\frac{n_{neff}^2}{2}\right) \cdot \left[P_{12} - \sigma\left(P_{11} + P_{12}\right)\right]\right\} \cos\left(\omega_s t\right) \tag{3}$$

In which, P_{ij} and σ are the elastic optical coefficient and Poisson's ratio of fiber grating materials respectively.

Therefore, when the acoustic wave acts on the grating, the wavelength of the fiber Bragg grating is:

$$\lambda_B(t) = \lambda_B + \lambda_B \varepsilon_m \left\{1 - \left(\frac{n_{neff}^2}{2}\right) \cdot \left[P_{12} - \sigma\left(P_{11} + P_{12}\right)\right]\right\} \cos\left(\omega_s t\right) \tag{4}$$

Therefore, the acoustic signal can be reflected through the change of wavelength.

3. Design of Optical Fiber Acoustic Sensor

The overall design of the arc discharge acoustic signal sensor is shown in Figure 3. The devices in the optical path include lasers, circulators, photodetectors, fiber gratings and signal acquisition devices. The light emitted by the laser source is transmitted to the grating through the circulator, and the light of a specific wavelength reflected by the grating enters the circulator again, and enters the photodetector to convert the optical signal into an electrical signal, which is collected and stored by the signal acquisition system for later data processing.

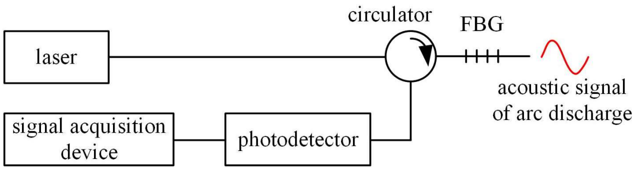


Figure 3. *Overall design diagram of arc discharge acoustic signal sensing detection system.*

3.1. Source

Laser plays a crucial role in the design of arc discharge acoustic fiber optic sensing detection system, and the selection of laser is critical for the normal and stable operation of the entire optical path in a long time. Once the stability of the laser in the working process does not meet certain requirements, the fluctuation of the optical power will cause errors in the accuracy of the photodetector in the system to receive the optical signal, which will affect the signal acquisition system's perception of the acoustic signal, and ultimately lead to errors in the frequency band range of the received arc discharge acoustic signal. The S4FC fiber laser with a wavelength of 1310 nm is selected in this paper, as shown in Figure 4, which is easy to couple and control the fiber driven by the laser diode. In order to achieve the best demodulation effect of the reflective spectrum of the sensing fiber grating under the action of the laser, the output optical power is set to be 5mW~7mW.

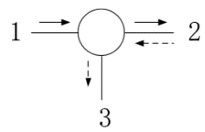
Figure 4. *S4FC1310 fiber laser.*

3.2. Fiber Bragg Grating

1310 nm and 1550 nm are the two wavelengths with the lowest transmission loss. Combined with the synergistic effect of fiber laser, 1310 nm fiber grating is selected in this paper. The center wavelength of the fiber grating is 1310.05 nm, the length of the grating area is 10 mm, the 3 dB bandwidth is 0.25 nm, the reflectivity is greater than 85%, and the period of the grating is 452 nm. The FC/PC connector is used to reduce the loss of optical power at the interface connected with the fiber grating in the optical path, so that the optical signal can be transmitted to the maximum extent in the fiber. Since the transformer is immersed in oil, it is easy for the fiber grating to fracture, so the fiber grating is packaged with organic glass to facilitate its placement in the transformer.

3.3. Optical Fiber Circulator

Optical fiber circulator is a kind of passive device using Faraday effect of magneto-optical crystal, which has the non-reciprocity of multiport input and output. The incident light of the optical fiber circulator is output from a certain port, while its reflected light is output from another specific port. For a 3-port optical fiber circulator, the input optical signal of port 1 can only be output from port 2, and the input optical signal of port 2 can only be output through port 3 after reflection. The basic structure of the optical fiber circulator is shown in Figure 5.



(a) Basic structure

(b) Physical photo

Figure 5. *Optical fiber circulator.*

The performance parameters of the optical fiber circulator used in this paper are shown in Table 1. In the whole optical path, in order to transmit optical signals with maximum efficiency, all three ports of the optical fiber circulator use FC/PC connectors. In combination with the working wavelength of the laser used in this research, the optical fiber circulator is selected as 1310 nm. The optical fiber circulator mainly plays a certain role as a bridge for the optical signal transmission in the entire optical path, and guides the optical signal sent by the laser in a specific direction.

Table 1. *Performance parameters of optical fiber circulator.*

operating wavelength	maximum optical power	isolation	insertion loss
1310±20 nm	500 mW	45 dB	0.8 dB

3.4. Photodetectors

According to the requirements for the response frequency band of the detector in the optical fiber acoustic sensor, combined with the laser used and the working wavelength of the fiber grating in this system, the PDA10CS2 InGaAs photoelectric detector is selected as the photoelectric conversion unit in the optical fiber acoustic sensing system.

The performance parameters of the PDA10CS2 detector are shown in Table 2. According to the sensing band range of the optical fiber sensor for the arc discharge acoustic signal, the gain is selected as 30 dB, under which the acoustic signal response is highest. Photodetectors can more strongly receive light signals near 1310 nm, and can transmit both audible and ultrasonic signals at the same time.

Table 2. *Performance parameters of photodetector.*

wavelength response range	3dB bandwidth	effective contact area	gain adjustment
900~1700 nm	300 kHz	0.8mm^2	0~70dB

3.5. Signal Acquisition Device

The signal acquisition device and the photodetector are connected through coaxial cable. The signal acquisition device in this paper uses a digital signal oscilloscope, which can realize the acquisition of acoustic discharge signals, and transmit the collected data to the computer for storage, as shown in Figure 6, and its parameters are shown in Table 3. When the acoustic signal acts on the fiber grating, the oscilloscope will display the time domain waveform. From the initial stage of arc discharge, the arc sound can be obviously heard. During this period, the waveform change of the acoustic signal can be observed through the oscilloscope. From the initial stage of the arc fault to the serious fault, the frequency of the acoustic signal generated by the arc discharge is changing with the passage of time. By storing the time domain waveform of sound information and analyzing and processing the signal, the frequency information is obtained to indirectly reflect the development severity of arc discharge.

Table 3. *Parameters of digital oscilloscope.*

bandwidth	number of channels	sampling rate	ADC digits
200 MHz	2	2 GS/s	8 bits

Figure 6. *Digital signal oscilloscope.*

3.6. Calibration Test of Optical Fiber Acoustic Sensor

The calibration test platform of optical fiber acoustic sensor is shown in Figure 7. Piezoelectric SR40M and SR10B narrowband low-frequency acoustic sensors are used as acoustic transmitters, and their frequency ranges are respectively 15kHz - 70kHz and 1Hz - 15kHz. The signal generator and narrowband low-frequency acoustic sensor are directly connected to form an acoustic emission device. The tests are as follows: apply an appropriate amount of couplant on the bottom of the fiber grating sensor and place it on the inverted narrowband low-frequency acoustic sensor.

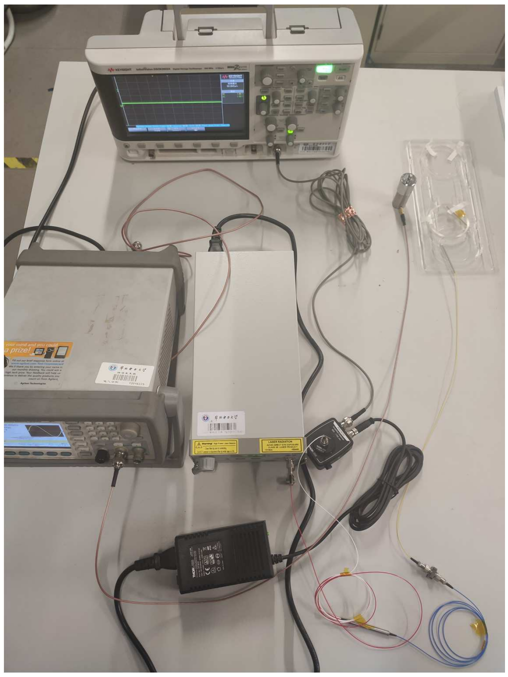


Figure 7. *Calibration platform of optical fiber acoustic sensor.*

Then place a weight above the fiber grating sensor to fully couple the fiber grating sensor with the narrowband low-frequency acoustic sensor. Set the excitation conditions of the signal generator: the waveform is a sine wave, the voltage is 10 V. Then adjust its frequency output, start the signal generator and observe the waveform of the oscilloscope. For example, when the output frequency of the signal generator is 50 kHz, the signal collected by the oscilloscope is a sine wave with a frequency of 50 kHz, as shown in Figure 8. We constantly change the output frequency of the signal generator and observe the signal frequency collected by the oscilloscope. We find that the frequency that the oscilloscope can receive is 1 kHz – 60 kHz. Therefore, the fiber grating acoustic sensor can effectively sense the frequency within the range of 1 kHz - 60 kHz.

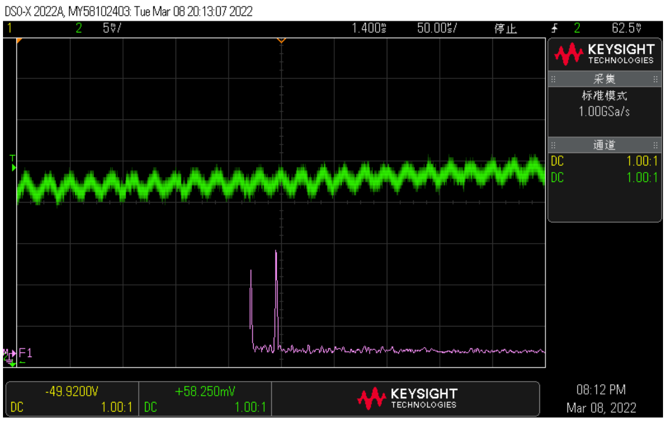


Figure 8. *Waveform observed by oscilloscope.*

4. Stress-Temperature Cross Sensitivity of Fiber Bragg Gratings

In order to solve the problem of grating stress temperature cross sensitivity, based on the existing test conditions in the laboratory, this paper chooses to use two basically identical fiber Bragg gratings, one as the reference fiber grating and the other as the sensing fiber grating to achieve temperature compensation for the fiber acoustic sensing system. The overall structure diagram is shown in Figure 9.

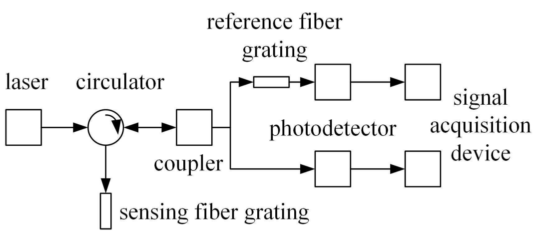


Figure 9. *Overall structure of optical fiber acoustic sensor.*

The light from the laser source arrives at the sensing fiber grating through the fiber circulator, and the light meeting the fiber Bragg grating returns from the sensing fiber grating to the fiber circulator, and then enters the fiber coupler; After passing through the fiber coupler, the light is evenly divided into two paths. One path of light enters the photodetector after passing through the reference fiber Bragg grating, and the other path of light directly enters the photodetector.

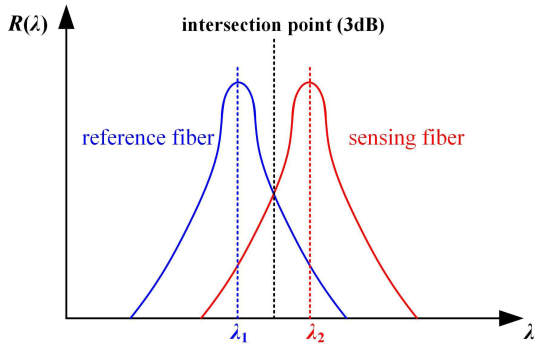


Figure 10. *Schematic diagram of fiber grating matching temperature compensation.*

In the optical fiber acoustic sensing system, the coupler is a 3 dB optical fiber coupler with a split ratio of 50:50, that is, a beam of light is divided into two beams of light with the same power and transmitted to different optical paths. In order to improve the reliability and accuracy of the built-in fiber-optic acoustic sensor for online monitoring of arc discharge, the double fiber grating structure is adopted. The reference fiber Bragg grating is matched with the sensing fiber Bragg grating, as shown in Figure 10, that is, the 3 dB point of the reference fiber grating intersects the 3 dB point of the sensing fiber grating, and the reflection ratio, side mode rejection ratio, 3 dB bandwidth and other parameters of the two gratings are basically the same, in order to realize real-time self-compensation of temperature. The influence of temperature on sensing fiber Bragg grating sensor can be minimized; In addition, the optical fiber acoustic sensor is of contrast type, that is, it collects two channels of signals at the same time and makes a difference between the two channels of signals, which can eliminate the common mode interference generated by the system laser source, photoelectric detector and other equipment. It improves the signal to noise ratio, and has high sensitivity detection capability for arc discharge acoustic signals with weak amplitude.

5. Measurement and Verification

The structure diagram of the acoustic signal sensing test of arc discharge inside the transformer and the arc discharge model in oil are shown in Figure 11 and Figure 12 respectively. The audible acoustic sensor, ultrasonic sensor and optical fiber acoustic sensor are respectively used to monitor the acoustic signal. The oil tank is simulated by the cavity and the cavity is made of epoxy resin. The height is 30 cm, the inner diameter is 16 cm, and the outer diameter is 20 cm. The arc discharge model selected for this test is the pole electrode model. In the test, the high-voltage electrode is directly connected to the high-voltage side of the transformer through the guide rod, suspended in the chamber, and the low-voltage side electrode is directly grounded.

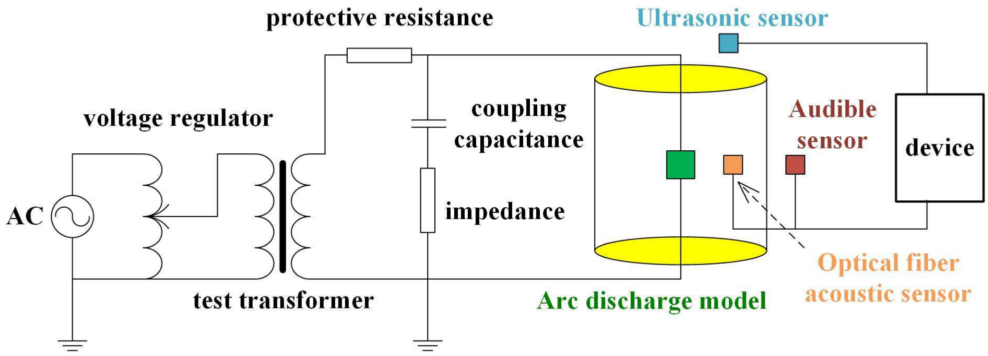


Figure 11. *Structure diagram of acoustic signal sensing test for arc discharge in transformer.*

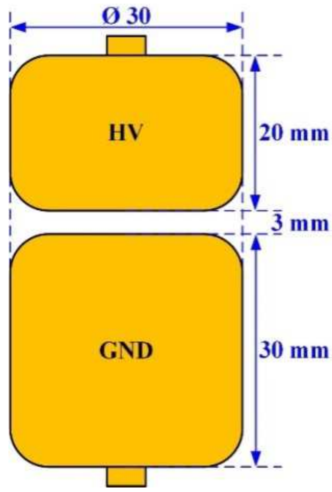


Figure 12. *Model of arc discharge in oil.*

The cavity is filled with pretreated oil, the optical fiber acoustic sensor is placed inside the transformer and immersed in oil. The SR40M ultrasonic sensor and audible acoustic sensor are placed outside the cavity, and the ultrasonic sensor is located at the upper part of the cavity. During the test, the position of the arc discharge model needs to be adjusted to make it at the same level with the optical fiber acoustic sensor and audible acoustic sensor.

The audible sensor used in this paper is a microphone, and its performance parameters are shown in Table 4. The discharge acoustic signal monitored by the audible sensor is shown in Figure 13. The experimental results show that due to the performance of the audible sound sensor itself, it is no longer able to sense the acoustic signal above 20 kHz. The sensing band that is more sensitive to the detection of audible discharge signal in oil is mainly 20 Hz - 8 kHz. The audible sound signal is used to judge the discharge state and block the fault.

Table 4. *Performance parameters of audible sensor.*

sampling rate	frequency response	sensitivity	signal-to-noise ratio
48 kHz	20 Hz~20 kHz	4.5 mV/Pa	100 dB

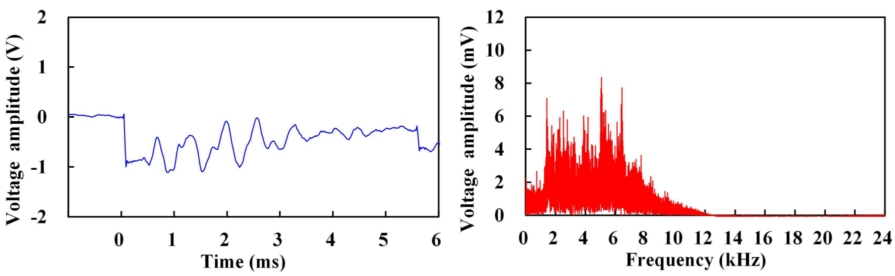
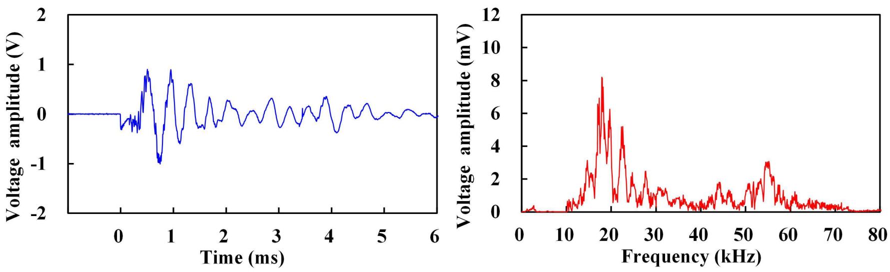


Figure 13. *Audible sensor sensing sound signal test.*

In order to monitor the ultrasonic low-frequency signal as accurately as possible, SR40M is selected as the ultrasonic sensor, and its performance indicators are shown in Table 5. The discharge acoustic signal monitored by the audible sensor is shown in Figure 14. The experimental results show that the sensing frequency bands of SR40M ultrasonic sensor for the acoustic signal of discharge in oil are mainly distributed in two ranges, namely, 15 kHz - 25 kHz and 50 kHz - 60 kHz.

Table 5. *Performance Parameters of Ultrasonic Sensor.*

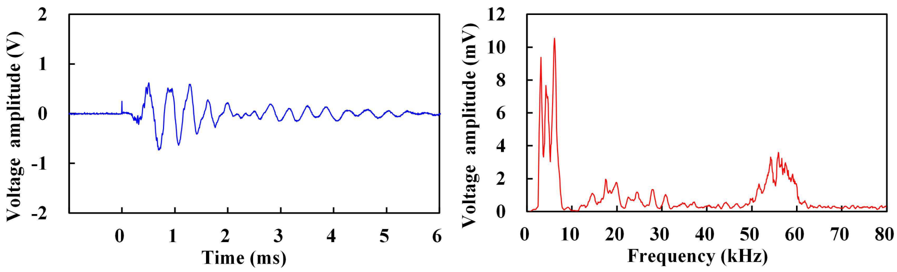
operating temperature	interface type	frequency range	sensitivity peak
20~120°C	M5	15~70 kHz	>75 dB



(a) Time domain (b) Frequency domain

Figure 14. *Ultrasonic sensor sensing sound signal test.*

The acoustic signal of discharge in oil sensed by the optical fiber acoustic sensor is shown in Figure 15. The experimental results show that the sensing frequency bands of the optical fiber acoustic sensor for the acoustic signal of discharge in oil are mainly distributed in two ranges, namely, 2 kHz - 10 kHz and 50 kHz - 60 kHz.



(a) Time domain (b) Frequency domain

Figure 15. *Optical fiber acoustic sensor sensing sound signal test.*

6. Conclusion

In this paper, the development and testing of the fiber optic acoustic sensor for the audible sound and ultrasonic low-frequency signal of arc discharge in transformer are carried out, and the conclusions are as follows:

(1) The structure of the optical fiber acoustic sensor built in the transformer is designed. The optical fiber acoustic sensor can be built in the transformer; A double fiber grating temperature compensation method is proposed, which can effectively reduce the influence of temperature on the sensor; The theoretical measurement range of the built-in optical fiber acoustic sensor is 1 kHz -60 kHz, giving consideration to audible and ultrasonic signals, and meeting the monitoring requirements for the acoustic signal of arc discharge.

(2) Three different acoustic sensors are used to measure the frequency range of arc discharge under the test conditions, and the measurement range of the optical fiber acoustic sensor is tested and verified. The acoustic signal frequency band perceived by the audible acoustic sensor is mainly 20 Hz - 8 kHz, the acoustic signal frequency band perceived by the SR40M ultrasonic sensor are mainly 15 kHz - 25 kHz and 50 kHz - 60 kHz, and the acoustic signal frequency band perceived by the optical fiber acoustic sensor are mainly 2 kHz - 10 kHz and 50 kHz - 60 kHz. The acoustic sensor can effectively realize on-line monitoring of arc discharge.

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