Research on pattern recognition technology for a high-performance optical fiber vibration sensor

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Abstract: In this paper, the optical fiber vibration sensor based on Mach-Zehnder Interference (MZI) principle is designed and researched, which can improve the ability to recognize the physical intrusion events for underground power pipelines by means of pattern recognition technology. Through data collection, analysis and processing, the vibration event database of key intrusion events in typical environment is established. By using coherent optical beat frequency, vibration recognition algorithm, machine learning and other technologies, the frequency domain diagram and time domain diagram of different vibration signals are analyzed and judged. In the end, the feature values of optical fiber vibration sensor such as frequency range, amplitude and waveform density are extracted.

1. Introduction

The buried power cables are developing towards high density and long length with the accelerating pace of urban reconstruction. However, shallow buried power cables installed on both sides of urban roads are easily damaged by various external forces, which causes great threat to life, property and social economy. The traditional monitoring system analyzes and judges the types of intrusion events with low accuracy rate and high false alarm rate, which brings great challenges to the prevention of external intrusion in underground power pipelines [1-3].

In this paper, the abnormal vibration signals along the underground power pipelines are detected using the optical fiber vibration sensor based on M-Z optical fiber interference principle, acquired and processed using coherent optical beat frequency technology and vibration identification algorithm. And the frequency domain diagram and time domain diagram of vibration signals are analyzed to extract feature values. Then, the intrusion event identification model is established using machine learning method, which can improve the recognition ability of optical fiber vibration sensor to physical vibration intrusion event[4-5].

2. Material and Methods

2.1. Composition and Principle of the Optical Fiber Vibration Sensor

The optical fiber vibration sensor uses three single-mode fibers in a fiber cable laying along the same channel as a sensor[9]. The fiber 1 and fiber 2 are used to test the vibration signal of the fiber, and the fiber 3 is used to transmit the signal. When external vibration occurs, the refractive index and length of the fiber core will change, resulting in the change of phase in fiber. Then, through the data acquisition, analysis, processing and feature value extraction of vibration signals in intrusion events, the vibration event database is established to recognize the physical vibration intrusion. The principle is shown in Fig. 1,
The laser source launches two beams of light. When the two beams are subjected to external shock or vibration during transmission, the refractive index of the fiber at the vibration point will change, resulting in the change of the optical wave phase. Due to the different spatial position, the phase modulation will be different, which changes the phase difference between the two beams. When the two beams reach the coupler 2, the phase difference will cause the change of interference fringe intensity. Then this signal can be detected by photoelectric conversion, data acquisition and signal processing. After demodulation, the detector restores the vibration wave signal, which basically reflects the waveform of the event. Compared with the waveform of the existing event library, the type of vibration source can be distinguished.

2.2. Coherent Beat-frequency Technology
When two beams of light whose wavelength difference is far less than the magnitude of wavelength (the frequency difference is very small) propagate in the same direction, the light with short wavelength will modulate the light with long wavelength, and form an envelope of the light intensity change. This phenomenon is called optical beat-frequency. The principle is shown in Fig. 2,

Optical fiber vibration sensor adopts coherence beat-frequency technology. It means that two lasers with approximate wavelengths are used to generate coherence, and the beat wavelength is controlled by slightly changing the wavelength difference below, which is easy to control the coherence sensitivity and achieve large dynamic range of unsaturated detection. The detection signal is unified to obtain the linear reduction of weak mechanical vibration waveform and the minimum signal can be detected by optical phase modulation and coherent detection [6-7].

2.3. Collection and Analysis of Data
The collection of data can be achieved in the acquisition module of the optical fiber vibration sensor, after wavelet filtering to suppress the background noise, the upper computer processes relevant data information by algorithm. Then, set a threshold to determine whether to alarm. When the data value is
greater than the threshold, the system alarms. When the data value is less than the threshold, the system does not alarm.

2.4. Extraction of Feature Value

The vibration signal of intrusion event is in the ‘time domain’, that is, x axis is time (seconds or minutes), and y axis is the measured vibration amplitude (displacement, velocity, acceleration). Based on this concept, displaying vibration waveform is a great accurate method. This method can show the actual vibration form of intrusion event and analyze its various vibration parameters. Compared with the vibration spectrum collected in the ‘frequency domain’, this vibration waveform can more accurately locate the duration, vibration amplitude and the number of vibration behaviors in the same period of an intrusion event. Moreover, it is not necessary to take the average value of the high-frequency part of the spectrum from the system, and then compare it with the data of the event database to make a decision [8-10].

The vibration waveform is analyzed by waveform amplitude, amplitude threshold, duration and other parameters to distinguish between false alarm and threat intrusion. Although the waveform caused by knock vibration of accidental events such as branches, birds, small animals, hail, wind and rain and the waveform caused by human invasion are similar, after verification and analysis by machine learning and AI recognition system, the two waveforms are different in terms of the overall waveform amplitude, duration and the number of events generated at the same time.

Optical fiber vibration sensor uses time domain/frequency domain hybrid analysis method and combined with artificial intelligence recognition technology to analyze the phase of coherent signals in order to achieve accurate classification and recognition of vibration source signals, which greatly improves the accuracy of vibration source recognition.

Based on the research on the linear reduction of distributed optical fiber vibration sensing signal and the identification of vibration source type, the method proposed in this paper takes the power communication cable connected to the optical fiber vibration sensing instrument as a long-distance sensor, perceives the vibration signal along the line, collects the GPS coordinate data along the line, and draws the GIS electronic map of the line (several lines).

Through the collected signals of a variety of vibration sources, such as power cables and pipelines drilled by manual tools, power cables and pipelines operated by large machines and the lifting of pipe covers, the vibration event database of power cables and pipelines is established and enriched based on the linear reduction of optical fiber micro-vibration distribution signals and the vibration event data (waveform diagram) of vibration source types, and the classification and data archiving of different vibration events are formed.

2.5. Establishment of Recognition Model

Any complex signal is composed of multiple short-time simple signals of complex algorithm, and the amplitude related to time is broadened and compressed.

- Construct the data mode by the maximum and minimum values of the signal which are selected according to the data, recognition effect and the number of segments.
- Calculate the Euclidean distance between the data and the model, and the model with the shortest Euclidean distance is regarded as the optimal data model.
- Input the parameters of all the optimal models to the system as the criteria for machine learning and learning.
- Compute multiple sets of data of various types by the established data model.
- Train the input signal and the expected output signal by machine learning method. When the minimum variance of the input signal and output signal after training meets the requirements, the training is stopped.

The system collects the vibration signal of physical intrusion events, and converts the photoelectric signal into the corresponding vibration event waveform. Through analysis and research, various intrusion events in typical environments are simulated, and the corresponding vibration waveform dia-
grams are collected. Then the vibration waveform diagram of intrusion events is defined and classified, according to the principle of big data analysis, which realizes the machine learning function.

3. RESULTS
Our company tested the 110KV and 10KV transmission cable lines from Tianxin substation to public service station, and from Tianxin station to Pingshi station, in Huadu District, Guangzhou, in the morning of July 12, 2019.

When the transmission line is subjected to external forces, such as hand digging, machine mining, cable along with the transmission line will provide vibration signals to the host computer room, sending warning information to make the staff timely to the scene to stop the destruction.

After the actual monitoring of the signal that produced by opening well cover, hand digging, heavy machinery operation or rainfall by the optical fiber vibration sensor, the waveform of the open well cover in Fig. 4, the waveform of manual tool excavation in Fig. 5, the waveform of heavy machinery operation in Fig. 6 and the waveform of heavy rain in Fig. 7 are obtained.

Figure 3. Waveform of the signal produced by opening the well lid

Figure 4. Waveform of the signal produced by hand digging

Figure 5. Waveform of the signal produced by heavy machinery operation
4. DISCUSSION

From the analysis of Fig. 3, Fig. 4, Fig. 5, Fig. 6, we can found that the vibration amplitude caused by different reasons is quite different. Through the analysis of waveform amplitude, amplitude threshold, duration, waveform density and other parameters, we can distinguish whether the vibration signal is an intrusion with false alarm or a threat. At the same time, the relevant parameters are used as the basis for pattern classification.

In order to verify the above analysis, 100 tests were carried out on the invasion behaviors of open well cover, hand digging, heavy machinery operation and rainfall. The test results are shown in Table 1.

| Intrusion classification | Testing times | Success times | Recognition rate |
|-------------------------|---------------|---------------|------------------|
| Opening well cover      | 100           | 98            | 98%              |
| Hand digging            | 100           | 96            | 96%              |
| Heavy machinery operation | 100           | 98            | 98%              |
| Rainfall                | 100           | 96            | 96%              |

From the test results in Table 1, it can be seen that the recognition rate of the pattern recognition technology of the optical fiber vibration sensor based on the M-Z fiber interference principle is greater than 96%. The algorithm, model and feature values that related to pattern recognition and the waveform discrimination standard of intrusion events, which meet the requirement of optical fiber vibration sensor and can be used as the basis for pattern recognition of optical fiber vibration sensor.

5. CONCLUSIONS

In this paper, an optical fiber vibration sensor based on the principle of M-Z optical fiber interference is designed. The direct buried single-mode communication cable is used as the detection sensor of the optical fiber vibration sensor. Optical fiber vibration signals are analyzed by coherent beat-frequency technology. The frequency domain and time domain diagrams of different vibration signals are analyzed and judged. And the characteristic values, such as waveform amplitude, duration and waveform density, are extracted to distinguish different intrusion events. Through experiments, we can found that the pattern recognition rate of the invasion event of the power buried pipe gallery can reach more than 96 % by using the optical fiber vibration sensor, which meets the requirements of the pattern recognition of the optical fiber vibration sensor. And the related technologies can be used as the basis for the pattern recognition of the optical fiber vibration sensor. In summary, the pattern recognition technology of optical fiber vibration sensor based on M-Z optical fiber interference principle provides an effective method, which can reduce the false alarm rate of buried pipe gallery against external damage.
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References
[1] Pei Yuanlong. (2017) Application of external force damage prevention monitoring system in transmission lines. J. Theoretical Research in Urban Construction., 24: 9.
[2] Sun Xiaodong, Ren Xiaoxia, Wang Lin. (2016) Present development situation of optical fiber vibration sensing technology. J. Industrial Instrumentation & Automation., (02): 21-25+63.
[3] Huang Hongbing, Zhang Chen, Jiang Zhengde, Yang Yongfeng. (2017) Research on the Intelligent Monitoring System of the Optical Cable Operation State. J. Electric Power Information and Communication Technology., 15(03): 101-106.
[4] Wu Feilong, Xu Jie, Zheng Xiaoli, Yang Lifan, Li Yongqian, Lv Anqiang. (2016) Research and Application of Optical Fiber Sensing Technology in the Submarine Cable Monitoring. J. Electric Power Information and Communication Technology., 14(03): 72-76.
[5] Wu Ruidong, Wang Yu, Wang Dong, Tan Jinlong, Liu Xin, Jin Baoquan. (2017) Embedded Design of Phase Modulation Module for Optical Fiber Vibration Sensing System. J. Chinese Journal of Sensors and Actuators., 30(02):200-205.
[6] He Weili. (2017) Analysis of Power Communication Cable Operation and Maintenance and Effective Measures to Prevent External Damage. J. Telecom World., (19):227-228.
[7] WANG Wenbo, HU Jinlei, ZHANG Zhemin, ZHANG Kun. (2018) Substation Geological Foundation Settlement Monitoring Based on Distributed Optical Sensing Technology. J. Guangdong Electric Power., 31(09):142-147.
[8] Zhou Zhengxian, Xiao Shilin, Tong Fangxuan. (2009) A positioning fiber-optic vibration sensor based on M-Z interference principle. J. Study on Optical Communications., (05):67-70.
[9] Sun Qizhen, Liu Deming, Wang Jian. (2007) A novel distributed optical fiber vibration sensing system based on ring structure. J. Acta Physica Sinica., (10):5903-5908.
[10] Tang Lin. (2006) Design of a Strain Measurement System Based on a Fiber Optical Interferer Sensor. D. Nanjing University of Aeronautics and Astronautics.