Research on Automatic Cable Monitoring System Based on Vibration Fibber Optic Sensor Technology

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Abstract. To ensure the safety of power cables, temperature monitoring of power cables is critical. In view of the shortcomings of some optical fibre measurement products, a long-distance distributed optical fibre sensor is proposed, which has the advantages of high measurement sensitivity, fast response speed, low false alarm rate, large measurement length, and stable operation. The distributed optical fibre vibration sensing measurement equipment is used to monitor the vibration signals along the cable in real time, and the signal changes before and after the breakdown fault are visually displayed by the patio-temporal spectrum diagram, and the vibration signal of the breakdown point is analysed in time and frequency. The performance of the system was tested, and the experiment verified that the temperature measurement accuracy error range of the temperature measurement system is about ±5 °C, and it has good stability. At the same time, the positioning accuracy is very high, and the fault point can be accurately located. This can avoid the occurrence of cable accidents.

1. Introduction

Power cable is an important carrier of power transmission. However, human factors (such as construction excavated skin, cut skin, etc.) and natural disasters (such as landslides, landslides, foundation settlement, corrosion, mouse damage, etc.) will cause cable line failures and affect the performance of the power grid construction. Therefore, it is very urgent and necessary to apply scientific methods to detect and locate the faults of power cables and promptly remind line maintenance personnel to take preventive measures in advance. Optical cable fault location usually uses the optical time domain reflectometer (OTDR) to measure the length of the fault point. This technology uses the precision photoelectric integration made by the Rayleigh scattering of laser light transmitted in the optical fibre and the backscatter generated by the Fresnel reflection. The instrument is widely used in the maintenance and construction of optical cable lines. It can measure the length of the optical fibre, the transmission attenuation of the optical fibre, the attenuation of the connector and the fault location. However, this technology cannot distinguish the specific material of the vibration point. In engineering practice, the location of the optical cable breakpoint is first measured by the OTDR, and the actual measurement is carried out through the redundant ratio between the ground and the cable laying process. After cutting, use OTDR to continue the measurement until it approaches the break point of the optical cable. This method has low working efficiency. It needs to excavate and cut
the optical cable multiple times during the process of finding the break point, which increases the workload [1].

This paper studies intelligent monitoring technology based on the principle of distributed optical fibre vibration sensing, and uses optical fibre sensing technology to carry out all-round real-time intelligent monitoring and positioning of power cable line faults in the power grid. The intelligent monitoring system can realize the detection and location of power cable line faults to ensure the safe and efficient operation of the power grid; comprehensively analyse and process the information of each sensor, and when abnormal conditions occur, take certain measures to guarantee by controlling the corresponding linkage equipment The power grid is operating normally.

2. The principle of distributed optical fibre vibration sensing technology

We focus on the principle of Raman scattering. In any molecular medium, spontaneous Raman scattering transfers a small part (generally about) of the incident power from one beam to another beam down shifted by the frequency. The vibration mode of the medium is determined, and this process is called the Raman effect. The interaction between excited photons and fibre molecules is divided into elastic collisions and inelastic collisions. During an elastic collision, no energy is exchanged between the photon and the molecule, so just changing the direction of the photon's movement does not change the wavelength of the excited photon (i.e., the energy of the photon); during the inelastic collision, the interaction between the photon and the molecule There is energy exchange, and photons can release or absorb molecules, which appear in the frequency domain as Stokes scattered photons and anti-Stokes scattered photons [2]. The interaction between photons and molecules can be represented by molecular energy level diagram 1.

![Schematic diagram of the energy levels of Raman scattering](image)

**Figure 1.** Schematic diagram of the energy levels of Raman scattering

When a molecule of energy level is excited to the virtual state of $E_i + hv_0$ by a laser photon, and then returns to energy level $E_1 (E_1 = E_i + h\Delta v)$, a photon with a frequency of $v_0 - \Delta v$ is scattered. This scattering is called Stokes scattering; while molecules originally at level $E_i$ Excited by the laser photon to the virtual state of $E_2 + hv_0$, and then back to the energy level $E_1 (E_1 = E_2 - h\Delta v)$, the photon with a frequency of $v_0 + \Delta v$ is scattered. This scattering is called anti-Stokes scattering. The Raman scattered light is composed of Stokes light and Anti-Stokes light. The wavelength shift is determined by the fixed properties of the fibre’s constituent elements, so the intensity of Raman scattered light is related to temperature, and its relationship formula:

Stokes light:
\[ I_s \propto \frac{1}{\exp(h \cdot c \cdot \Delta \gamma / k \cdot T) - 1} \cdot \lambda_s^{-4} \quad (1) \]

Anti-Stokes Light:

\[ I_a \propto \frac{1}{\exp(h \cdot c \cdot \Delta \gamma / k \cdot T) - 1} \cdot \lambda_a^{-4} \quad (2) \]

In the formula, \( \lambda_s \) and \( \lambda_a \) are the Stokes and Anti-Stokes light wavelengths respectively; \( h \) is Planck’s constant; \( c \) is the speed of light in vacuum; \( k \) is the Boltzmann constant; \( \Delta \gamma \) is the offset wave number; \( T \) is the absolute temperature.

In order to eliminate the effects of the unstable output of the laser tube, the bending of the optical fibre, the loss of the connector, etc., and improve the accuracy of temperature measurement, in the system design, the dual-channel dual-wavelength comparison method is adopted, that is, the Anti-Stokes light and the Stokes light are separately collected, and the temperature signal is demodulated using the ratio of the two intensities. Since the anti-stokes light is more sensitive to temperature, the anti-stokes light is used as the signal channel and the stokes light is used as the comparison channel. The intensity between the two is shown in Equation 3:

\[ R(T) = \frac{I_a}{I_s} = \left( \frac{\lambda_a}{\lambda_s} \right)^4 \cdot \exp(-h \cdot c \cdot \Delta \gamma / k \cdot T) \quad (3) \]

After transformation, formula 4 can be obtained:

\[ \frac{1}{T} = -\frac{k}{hc\Delta \gamma} \left[ \ln R(T) + 4 \ln \left( \frac{\lambda_a}{\lambda_s} \right) \right] \quad (4) \]

For a fixed temperature (calibration temperature of a constant temperature bath), it can be expressed by Equation 5:

\[ \frac{1}{T_0} = -\frac{k}{hc\Delta \gamma} \left[ \ln R(T_0) + 4 \ln \left( \frac{\lambda_a}{\lambda_s} \right) \right] \quad (5) \]

Formula 6 can be calculated from two equations:

\[ \frac{1}{T} = \frac{1}{T_0} - \frac{k}{hc\Delta \gamma} \left[ \ln R(T) - \ln R(T_0) \right] \quad (6) \]

It can be seen that after the calibration of the temperature measurement system, the temperature value along the measurement point of the optical fibre can be determined by measuring \( R(T) \).

3. Distributed optical fibre vibration sensing system

The optical fibre can be used to transmit information. When the optical fibre is disturbed, it can transmit the signal to the receiving detector. When the detected signal changes, the characteristics of the light propagating in the optical fibre also change, which can be obtained by detecting the
modulated light the change of external physical quantity is the basic principle of optical fibre sensing. The distributed optical fibre vibration sensing system is a modulated pulse laser emitted by a narrow linewidth laser light source and transmitted to the vibration detection fibre. When the parameter to be measured in the fibre changes, the phase information characteristics of the light propagating in the fibre will change. The transmitted or scattered light propagating in the optical fibre is transmitted through the optical fibre and finally reaches the photodetector, which converts the optical signal into an electrical signal and outputs it. Through the specific algorithm demodulation, the changes of these optical parameters can be calculated, and the function of measuring the change of the external environment physical quantity can be completed by the specific algorithm demodulation.

Generally, the linewidth of a narrow linewidth laser is less than 3KHz. The output wavelength of the narrow linewidth laser used is 1550.12nm. The narrow linewidth laser emits continuous laser light pulses after being energized. The output end of the laser is the fibre output. The continuous light pulses emitted by the narrow linewidth laser are transmitted to the acousto-optic modulator for modulation via the fibre connection. The laser pulses are modulated, and the pulse light is amplified by the erbium-doped fibre amplifier (EDFA) to amplify the input pulsed optical signal. The input light is amplified to increase the signal energy input to the detection optical cable, so that the detection distance is increased. The amplified pulsed optical signal is input to a 100GHz filter to filter out unwanted optical signals in the amplified pulse. The filtered optical signal is input to the input 1 port of the fibre circulator, and port 2 of the circulator is connected to distributed fibre vibration. The detection optical cable of the sensor system, the 3 ports of the circulator are connected to the avalanche photodiode (APD) to detect the coherent and Rayleigh scattered light intensity signal in the detection optical cable and convert it into a current signal. After entering the data acquisition card for data processing, the vibration signal on the detection optical cable is finally obtained, as shown in FIG. 2.

Figure 2. Optical path diagram of distributed optical fibre vibration sensing

4. Design of high-voltage power cable temperature monitoring system
The high voltage power cable temperature monitoring system is shown in Figure 3. The optical fibre temperature measurement engineering machine is mainly composed of an optical measurement unit and a demodulation unit, and the monitored optical signal is demodulated by the optical fibre temperature measurement engineering machine to realize temperature monitoring. The optical fibre temperature measurement engineering machine transmits the cable temperature to the background monitoring host. Its functions are mainly fault judgment, over-temperature alarm, and remote
monitoring and diagnosis. The function of the system monitoring software is to display the maximum temperature of each monitoring point in real time, draw the temperature change curve of the monitoring point, and form a statistical report. When the temperature exceeds the limit, it will alarm to remind maintenance personnel to handle the fault.

![High-voltage power cable temperature monitoring system](image)

**Figure 3.** High-voltage power cable temperature monitoring system

When there is vibration acting on the sensing fibre, due to the influence of the elastic light effect, the phase of the light at the vibration position changes, causing the phase change of the backscattered light at the corresponding position, and the interference intensity of the scattered light within the pulse width will also occur Phase change. The difference between the interference intensity curves of Ф-OTDR backward Rayleigh scattered light at different times is made, and the position on the difference curve where the light interference signal changes drastically corresponds to the position where the vibration occurs [3].

4.1. Technical indicators

The system is mainly composed of distributed optical fibre vibration host, detection fibre and monitoring host, as shown in Figure 4. Among them, the detection fibre adopts an existing single-mode fibre inside the submarine cable; the distributed fibre vibration host and monitoring host are set in the monitoring room at the end of the submarine cable line. The monitoring host is a PC, which runs the calculation and monitoring process and provides a monitoring view.

![Schematic diagram of submarine cable vibration monitoring system](image)

**Figure 4.** Schematic diagram of submarine cable vibration monitoring system

The key technical indicators are shown in Table 1. Single-mode fiber for general communication can be used as a sensor for distributed vibration measurement. The detection distance can be up to 50 km. It can resolve two simultaneous events at intervals of 10 m. The single-point sampling rate is 1 000 Hz, and the theoretical frequency limit can be identified It is 500 Hz.
Table 1. Key technical indicators of the system

| name                        | index                                      |
|-----------------------------|--------------------------------------------|
| Fiber type                  | 9/125 μm single-mode fiber                 |
| Detection distance          | 50 km                                      |
| Detection time              | 1 ms                                       |
| Spatial resolution          | 10 m                                       |
| Frequency Range             | 1 to 500 Hz                                |
| Positioning accuracy        | ± 10 m                                     |
| Event recognition method    | Pattern recognition, neural network        |
| MTBF                        | 50 000 h                                   |

4.2. Fault location method

The ground fault of power cable can be divided into two cases: the first is that the power cable discharges to the ground, but it does not damage the integrity of the surrounding optical cable, so the longitudinal positioning function of the distributed optical fibre vibration system can complete the fault location. Precise positioning: The first step is to turn on the power cable switch to discharge the cable to the ground, and generate vibration to the ground. The vibration of the ground causes the vibration alarm of the cable laying in the same trench, and the system discharge of the system to the ground is read through the system software; the second step The free-fall control system for shot puts the shot put around the ground discharge; the optical fibre vibration sensing system feels the vibration information, and by shooting the shot at the location of the optical cable, the point where the maximum vibration energy is found is recorded as the fault point of the power cable.

If the discharge process of the power cable causes the breakage of the optical cable laid in the same trench, the fault location needs to be located through the following process: the first step, the free-fall control system of the shot puts the shot around the broken cable, and the optical fibre vibration sensing optical path module Feel the vibration information, the fibre optic vibration sensor collection and processing module collects and analyses the vibration information on the detection cable and transmits the information to the computer; in the second step, the timing controller records the grounding time t0 of the free-fall of the shot, and records that the cable is broken on the computer. The point position reflects the moment of vibration t1; in the third step, the depth of the buried cable is d, the propagation speed of the vibration in the corresponding ground is v, and the height of the free-fall of the shot from the ground is h. The break point of the cable is calculated at The distance from the ground shot location A1 on the horizontal ground is a circle with a radius; the fourth step, repeat the above steps once, and the distance between the break point of the optical cable on the horizontal ground and the shot ground A2 is the circle with a radius of L2 On the fifth step, the two circles have two coincidence points, which are located on the coincidence point of the cable laying line It is the break point of the optical cable. In the sixth step, if the cable laying route is unknown, the third shot is thrown, and the distance of the broken point of the optical cable on the horizontal ground from the shot place A3 is a circle with a radius of L3. The overlapping point of the three circles is the break point of the optical cable [4].

5. Field test

5.1. Space positioning accuracy performance test

At each monitoring point, a heater is used to heat the optical cable, and the corresponding position of the temperature increase is recorded on the temperature-position curve, and then 8 points can be located. Comparing the position measured by the sensor and the actual position, the measurement error is 0.5 to 1 m.
5.2. Response time performance test
The fire protection of high-voltage power cables needs to be urgent. The faster response time can maintain equipment failure as soon as possible, so the response time of 8-point heating is very short [5].

5.3. Temperature test accuracy test
Put the optical fibre cable near the H point into several small circles and put it into a thermostat with a thermometer to accurately monitor the temperature change. Set the temperature of the thermostatic device. When it reaches the set temperature and keep it for a period of time, check the corresponding temperature value of the temperature-position curve and the value of the standard thermometer. The H point temperature test example is shown in Table 2.

| Sensor value / °C | Thermometer value / °C |
|-------------------|------------------------|
| 29.5              | 30.0                   |
| 34.0              | 35.0                   |
| 40.5              | 40.0                   |
| 43.5              | 45.0                   |
| 51.0              | 50.0                   |
| 53.0              | 55.0                   |
| 60.0              | 60.0                   |
| 65.0              | 65.0                   |
| 71.0              | 70.0                   |
| 74.5              | 75.0                   |

It can be seen from Table 2 that the difference between the test temperature of the sensor and the actual temperature is ± 1 °C.

5.4. Long-term running performance test
After setting the relevant data, the equipment will be operated continuously for 24 hours, and the tested temperature will be displayed on the temperature-position curve. The temperature measurement curve of distributed optical fibre sensor and thermocouple is shown in Figure 5.

Figure 5. Temperature measurement curve of distributed optical fibre sensor and thermocouple
Since point G is not buried with soil, its temperature changes greatly. It can be seen from Figure 5 that the thermocouple temperature measurement curve is not much different from the distributed optical fibre temperature measurement curve, but during the long-term temperature test, electromagnetic interference will occur in the test site, and the distributed optical fibre temperature measurement technology can overcome electromagnetic interference [6].

6. Conclusion
The cable fault location system based on the distributed optical fibre vibration sensing principle studied in this paper can accurately detect power cable faults and prevent failures due to power cable aging and other reasons. Stop transmission interruption caused by deliberate sabotage, theft, etc., so as to ensure the safety and smooth transmission of medium and high voltage power cables. When the power cable line fails, it automatically realizes early warning, automatically locates the location of the fault, and promptly informs the management personnel to effectively handle the alarm situation, thereby improving the reliability of power supply to the power grid.

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