How to Apply Distributed Optical Fiber Temperature System to Measure the Temperature of Cable

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Abstract: In order to discuss the prospect of distributed optical fiber temperature system applied in HV cable temperature on-line monitoring, the paper presents basic principles and characteristics of this system. The precision of temperature measurement, location, response time and reliability are examined through two-month field test. Test results show that the system has many advantages, including small error in temperature and location measurement, short response time, reliable operation and measuring the temperature in long distance and large area. The technology can be very effective in on-line monitoring of cable temperature and provide direct data for calculating cable ampacity. What is more, it can keep the fire away from fire.

Key words: distributed optical fiber temperature system, cable temperature, cable insulation, on-line monitoring, ampacity

Introduction

The average failure rate of Chinese grid cables is higher than that of some developed countries. One vital reason for higher rate is a lack of efficient on-line monitoring while temperature on-line monitoring is one of the most important aspects.

It is necessary to perform accurate and real-time temperature monitoring for installed cables and the environment to determine best and safest cable ampacity. Such accidents can be avoided if early warning is delivered through temperature measurement at the early stage of the accident and then countermeasures are taken at once.

The traditional method of measuring the temperature is to install thermal detectors such as thermocouple at the important position of cable to measure the temperature. This method can only measure the temperature of part of cable system not the whole cable. However, one or several optical fibers can monitor line-type equipment or point-type equipment which covers miles of ground via the distributed optical fiber temperature measurement system. The technology is used to conduct two-month on-site test for one 220kV electric cable installed in a UHV cable experiment room.

1. A Profile of Distributed Optical Fiber Sensor
The working principle of distributed optical fiber sensor is optical domain reflection (OTDR for short) and Raman scattering temperature effect. In other words, the sensor uses the OTDR system and Raman scattering effect to locate and measure the temperature respectively. After the laser light source in the main processor injects the impulse into the fiber, a small proportion of Raman scattering light (including Stokes Light and Anti-stokes light) would reflect along optical fiber. The relation between ratio of Anti-stokes Light photon strength to Stokes Light and temperature is shown in formula (1). The return time of Raman scattering light is obtained based on the formula (2). So the target distance is calculated.

\[
\frac{I_{as}}{I_s} \propto \exp \left( \frac{hc\sigma}{kT} \right) \tag{1}
\]

\[
l = \frac{vt}{2} \tag{2}
\]

Where:

- \( I_{as} \): photon strength of Anti-stokes Light
- \( I_s \): photon strength of Stokes Light
- \( s^{-1}/sr \)
- \( h \): Planck constant
- \( c \): speed of light in the vacuum, m/s
- \( k \): Boltzmann constant
- \( \sigma \): wave number, m\(^{-1}\)
- \( T \): absolute temperature
- \( v \): speed of transmission in the optical fiber, m/s
- \( t \): time difference between incident light and reflected light, s

\( k \): measured point distance, m

The main processor and control computer analyze and deal with Raman scattering light; then calculate the temperature and position of all points and at last output the diagram of temperature distribution of the whole fiber (the maximum is 30km).

The distributed optical fiber sensor is composed of 62.5/125 multi-mode fiber, laser, optical coupler, optical receiver, high speed data capture card and IPC, which is shown in Fig.1. Main technical indicators include measuring distance, spatial resolution, sample interval, location deviation, temperature error, temperature resolution, measuring time and range.

![Diagram of distributed optical fiber sensor](image)

Fig.1 Diagram of distributed optical fiber sensor

2. Test Content and Results

2.1 Test installation and on-site layout

The test was completed at the ultra-high voltage cable experiment room of Wuhan HV Research Institute. A section of 220kV electric cable with a length of about 140m was laid outside the experiment room, passing through simulation cable area, outdoor ground, cable tunnel, simulation well and burying. One end of temperature cable is inserted into optical fiber socket of main processor while the other end leads out from the experiment room and clings to the
outer sheath via rubberized fabric along the direction of cable. Key parts need to be twined more. They are represented by \( P_1-P_8 \) and the test layout is shown in Fig.2. The thermal coupler and distributed optical fiber sensor are installed at these parts to measure the temperature at the same time. Then results are compared. The data obtained through thermal coupler is displayed at the other computer by means of other methods.

![Diagram](image)

**Fig.2 Test diagram**

1 simulation cable area: 1 SMA
2 cable terminal A- tunnel: 2CTA-T
3 cable tunnel area: 3CTA
4 simulation well area: 4SWA
5 cable buried area: 5 CBA
6 simulation well area: 6SWA
7 cable tunnel area: 7CTA
8 tunnel-cable terminal E: 8TCTE

2.2 Test items and data

(1) Space location precision performance test

Use the heater to heat eight parts of the cable and then the temperature rises correspondingly. Mark temperature-rise positions on the temperature-position curve diagram to locate eight points. Compare measuring positions of sensor with actual positions and the measuring deviation is 0.6-0.9m.

(2) Response time performance test

As to cable and cable tunnel fireproof or alarming, quick measurement and short response time can win us precious chance of repair. The response time for eight points is short (4-6s). The software can set the upper limit of temperature or rising rate limit. If exceeding the limit, the device would sound the alarm.

(3) Temperature measuring precision test

Roll a section of cable near to \( P_8 \) into several circles and put them into a thermostat equipped with standard thermometer. Set the temperature of thermostat after cables are placed in the thermostat. Take readings after reaching the target and keeping for a while. Test results are shown in Tab.1.

Based on Tab.1, the difference between the temperature by sensor and that by standard thermometer is \( \pm 1 \)℃.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>29.5</th>
<th>34.0</th>
<th>40.5</th>
<th>43.5</th>
<th>51.0</th>
<th>53.0</th>
<th>60.5</th>
<th>65.0</th>
<th>71.0</th>
<th>74.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermometer</td>
<td>30.0</td>
<td>35.0</td>
<td>40.0</td>
<td>45.0</td>
<td>50.0</td>
<td>51.0</td>
<td>60.0</td>
<td>65.0</td>
<td>70.0</td>
<td>75.0</td>
</tr>
</tbody>
</table>

**Tab.1 Comparison of temperature measurement**

(4) Long-term running performance test

The equipment starts to run for 24h without pause after the completion of relevant setting. Measure the temperature and display on the temperature-position curve in a real-time manner; save the data automatically every 60 seconds (set the interval based on your demand);
record every 2 hours and 9 times for one day. The test duration is two months. Fig.3 shows the temperature curves of P5 and P7.

Fig.3 Comparison of test results

According to Fig.3, it is found that two groups of curves are basically consistent and the temperature measuring deviation is around 1°C, which shows that there is not great discrepancy between test result of distributed optical fiber sensor and thermal coupler. In the long-term performance test, thanks to the use of optical fiber, the equipment is not affected in service even though there is complex electromagnetic field interference at the test site.

3. Application of Cable Insulation On-line Detection

The breakdown of cable insulation is always accompanied by some special phenomena. For instance, there would be an abnormal rise in temperature at and around breakdown part. If detected in advance, measures can be taken to fix it.

Lay one electric cable with the diameter of 2.5mm on the surface of one 10kV XLPE single-core cable sheath; determine several key positions; equip both ends of cable with cable terminals and then apply power frequency voltage to the cable; raise the voltage at the speed of 1kV/min. When the voltage rises to 102kV, two wave peaks appear at 105m and 115m. As the voltage continues to rise, wave peaks become obvious and the amplitude is higher and higher. The cable breakdowns after 53min. The temperature is 33.4°C and 33.7°C and the temperature of other positions is between 21-22°C, which is shown in Fig.4. Inspect the cable upon the breakdown and it is found that the breakdown positions are consistent with two wave peaks positions.

Fig.4 Curve of cable temperature before breakdown

The test indicates that distributed optical fiber temperature measuring system provides a new method for cable insulation on-line monitoring.

4. Conclusions

The distributed sensor has remarkable characteristics: (1) it is easy to measure the temperature of long test object with a broad range; precision of temperature measurement and location is high; it is simple to install and use; the environment has minor effect on the sensor; its operation is stable and reliable. (2) The cable ampacity is determined by the temperature of cable conductor, which cannot exceed the limit. The temperature of
conductor is closely related to the cable structure and environmental conditions. Hence, the allowable ampacity of cable is determined by a series of parameters, such as soil temperature and thermal resistance. As to cables laid in complicated environment, the temperature of outer cable sheath is monitored in a real-time manner to calculate the temperature of conductor and then control the ampacity of cable. However, if the optical fiber is directly buried in the cable in production, it is easier to correctly determine the cable ampacity in actual application. (3) Its flexible alarming system can avoid the cable fire accident. (4) The test shows that the system plays a certain role in the detection of cable insulation and provides a new technical method.