Research and Application of Transmission Line Environmental Monitoring Based on Optical Fiber Sensing Technology

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Abstract. In this paper, the optical fiber sensing technology is taken as the research object. Firstly, according to the demand of the sensing layer of the power Internet of things, a transmission line environment online monitoring system is proposed based on the multi risk monitoring of external breakage, fire, icing, galloping and so on of the cable (overhead line), the composition and deployment of the monitoring system are introduced. Secondly, based on the research of temperature field and stress field distribution of optical fiber, combined with big data and artificial intelligence, the important environmental parameters of the line can be monitored. Finally, taking different monitoring scenarios as examples, this paper expounds the different monitoring functions of the environmental monitoring system of the Internet of things for transmission lines, which provides useful reference for environmental monitoring of transmission lines.

1. Introduction
In recent years, the transmission lines are often stopped due to the factors of wildfire, lightning and static electricity, external force damage and so on. The lines are aging, broken strand and other faults due to the effects of electricity, heat, mechanical load, etc., which threaten the safe and stable operation of the transmission lines[1]. Due to the wide geographical range of communication lines, it is necessary for the early warning system to have the ability of intelligent environment perception in the case of extra-long distance[2]. Power Internet of things has become an important research direction, and more sensor devices have played a special role[3]. At present, there is a lack of timeliness in the monitoring of hidden danger information, and the monitoring means fail to make full use of the advantages of (Optical Fiber Composite Overhead Ground Wire, OPGW) cable and transmission line laying, and can not fully perceive the important environmental parameters of power lines (overhead lines) and hidden danger information such as the situation of wildfires. With the development of distributed optical fiber sensing technology, many types of optical fiber sensors have been used in perimeter detection[4]. Through the environmental perception and early warning of the optical cable, the temperature field and stress field of the spare optical fiber core of the OPGW cable of the transmission line are monitored on line, and the intelligent sensing system of external rupture, fire,
Icing and galloping is built, which can monitor the important environmental parameters of the optical cable line in real time, detect the possible external damage, build the topological diagram of the optical cable line, and realize the intelligent management of the optical cable fault operation and maintenance. Through the prefabricated circuit topology template query and control test equipment, a series of (optical time domain reflector, OTDR) collection processes can be defined and carried out. Then the test information is collected into the monitoring host and server, and the topology information, test results and fault alarm information are combined, which are provided to different maintenance personnel according to the preset authority management plan of the system. Enhance the ability of optical cable and transmission line on the same tower to resist all kinds of natural disasters and external damage and the ability to allocate information resources to meet the needs of information communication in all aspects and different fields of power grid development, and strive to build a green environmental protection power optical cable communication network with advanced technology, good practicability, reasonable network structure, high reliability, full coverage, strong resistance and high comprehensive efficiency. The communication network can effectively enhance the reliability of the backbone communication optical cable, realize the rapid operation and maintenance, and provide safe and reliable optical line channel for power communication.

2. Transmission line risk
According to statistics, from August 2014 to May 2019, a total of 65 hidden dangers were dealt with for OPGW cable of 500kV transmission line, involving 18 transmission lines, including 35 hidden dangers of cable ground wire wear, 9 hidden dangers of wildfire, 6 hidden dangers of cable down lead disconnection, 6 hidden dangers of cable strand disconnection, 1 hidden danger of cable connector box loosening, 2 hidden dangers of lightning and static damage, and 6 other hidden dangers.

2.1. Hidden danger of line broken strand
The aluminum strand of OPGW of a 500kV Line was broken. In July 2017, at tower 169 of 500kV Line, it was found that the aluminum strand of OPGW optical cable was broken. There was a hidden danger in the operation of OPGW optical cable, which was recovered after defect treatment.

2.2. Line lightning and static damage
In August 2017, an over-voltage occurred at the exit optical cable of a 500kV substation at the position of optical cable led by the station frame, which led to the interruption of optical cable, affected the open-loop operation of optical transmission network, and the business channel of relay protection was interrupted. After emergency repair, the business recovered. The breakpoint of the fault optical cable is shown in Figure 1.

![Figure 1. Hidden Danger of Line Lightning.](image)

2.3. Hidden danger of line fire
A fire broke out in a 500 kV line area. At 2:52 on May 5, 2019, the team members reported to the dispatching of the transmission center on duty that there was a fire near towers 152-153 and 153-154 of the line. At 12:10 on May 5, it gradually went out. It is found that there are obvious discharge traces
at the place 4 meters away from the first spacer of phase B (central line) of line 152-153, as shown in Figure 2.

![Figure 2. Line Corridor Fire.](image)

2.4. Hidden danger of line icing
Most of the transmission lines are located in the cold mountainous area, which are often affected by natural factors[13]. In recent years, the abnormal winter climate has caused the ice damage accident of the transmission line and caused direct or indirect economic losses[11]. This kind of accident has the characteristics of long duration and wide coverage[10].

3. Principle of optical fiber sensing technology
Scholars at home and abroad have made some progress in the research of Brillouin sensing technology[5]. The on-line monitoring system of optical cable realizes the daily monitoring of optical cable by collecting the optical signal changes such as the external force damage, deformation, temperature rise and fall, etc. The optical fiber on-line monitoring system adopts the fiber Brillouin distributed sensing mechanism and Brillouin optical time domain reflection technology.

3.1. Fiber Brillouin distributed sensing mechanism
Because the temperature and strain sensed by the sensing optical fiber will affect the acoustic velocity inside the optical fiber, the temperature and strain sensed by the sensing optical fiber can be obtained by measuring the Brillouin frequency shift, and the calculation method is shown in formula (1).

\[
Bv = \frac{2nV_A}{\lambda}
\]  

(1)

The \( n \) is the refractive index of the fiber, \( V_A \) is the speed of sound, the \( \lambda \) is the incident wave length. When the fiber stress or surrounding temperature changes, the material properties of the fiber such as young's modulus, Poisson's ratio, refractive index, material density and thermal expansion coefficient will change accordingly, and the Brillouin frequency shift will change accordingly, and the change relationship is shown in formula (2) and formula (3).

\[
\epsilon = \frac{V_B(\epsilon)}{V_B(\epsilon)} + C_\varepsilon \epsilon
\]

(2)

\[
B_T = V_B(T) \left[ 1 + C_T(T - T_r) \right]
\]

(3)

The \( \varepsilon \) is the longitudinal stress of the optical fiber, the \( T \) is the temperature, the \( T_r \) is the reference temperature, the ratio coefficients of stress and temperature are \( C_\varepsilon = 4.6 \) and \( C_T = 4.6 \), the relationship between Brillouin frequency shift and temperature mainly comes from the change of sound velocity in optical fiber.

3.2. Brillouin optical time domain reflection technology
Brillouin OTDR technology uses the self published Brillouin scattering technology, which is similar to the technology of traditional OTDR system. The structure is shown in Figure 3.
The pulse light signal is injected into the optical fiber from one end of the sensing optical fiber through the circulator 1, and the Brillouin scattering light generated in the optical fiber is returned in the opposite direction and sent to the photo detector through the circulator 1, circulator 2 and fiber Bragg grating for processing in the data acquisition and processing system.

The back Brillouin scattering light intensity produced by a small section of optical fiber $dz$ with a distance from the front of the optical fiber is $z$, and its variation relationship is shown in formula (4), formula (5) and formula (6).

\[
dP_B(z, v) = g(v, v_B) \frac{c}{2n} p(z) dz \exp(-2\alpha z) \quad (4)
\]

\[
g(v, v_B) = \frac{g_0(\Delta v_B/2)^2}{(v - v_B)^2 + (\Delta v_B/2)^2} \quad (5)
\]

\[
z = \frac{ct}{2n} \quad (6)
\]

The $z$ is the distance from the front end of the fiber; $p(z)$ is the peak power of incident pulse light at $z$ point; $v$ is the frequency of Brillouin scattering light; $v_B$ is the frequency at peak gain $g_0$; $g(v, v_B)$ is Brillouin gain spectrum with Lorentz function; $c$ is the speed of light in vacuum; $n$ is the refractive index of the fiber; $\alpha$ is the loss coefficient of optical fiber; $\Delta v_B$ is Full Width Half Maximum of Brillouin gain spectrum; $t$ is the time interval between the incident light pulse and the backscattered light detected by the receiver.

When the stress or temperature changes in a certain region of the optical fiber, the Brillouin scattering spectrum will shift. The back Brillouin scattering will be measured by using the coherent receiver which mixes the local light and scattering light separated from coupler 1. This method is called Brillouin optical time domain reflectometer (BOTDR). The coherent receiver is only affected by shot noise and has high sensitivity. It can eliminate the Rayleigh scattering which is 20 ~ 30dB higher than Brillouin scattering, so as to obtain a sufficiently narrow frequency accuracy. BOTDR technology, using Brillouin laser coherent beat frequency local light, can solve the problem of weak signal detection, broadband frequency shift, can real-time monitor the temperature and strain information of power lines, and reflect the safety status of lines[6].

### 4. Research content of monitoring system

In view of the temperature field and stress field on-line monitoring of the free core of OPGW optical cable of a 500kV transmission line #1 line and #2 line, an intelligent sensing system against external breakage, fire, icing and galloping is built. In combination with cloud platform technology, the important environmental parameters of the optical cable line are monitored in real time, the possible external damage is detected, the topological diagram of the optical cable line is built, and the intelligent management of optical cable fault operation and maintenance is realized. At the same time, to enhance the safety and reliability of communication optical cable, the operation and maintenance
management has become intelligent and fast, providing a safe and reliable optical line channel for power communication. The monitoring system includes 1 set of monitoring terminal, and is equipped with GIS module, external failure monitoring module, fire monitoring module, ice covering monitoring module, dancing monitoring module, 1 set of network management server, cloud platform, operation and maintenance management system.

4.1. Perceptual acquisition
Aiming at the OPGW cable on-line monitoring system of #1 and #2 transmission lines, through the advanced optical fiber sensing technology, the temperature field distribution and stress field distribution of optical fiber are tested, the temperature field fire alarm analysis model, optical fiber stress field environment wind force cable stress field galloping risk analysis model are established, which directly reflects the environmental information of cable (overhead line) such as external rupture, fire, icing, galloping, etc. It makes online monitoring become an important part of the perception layer of the power Internet of things, which is integrated into the application of system level big data and artificial intelligence of the power Internet of things.

4.2. Perceptual acquisition
According to the needs of the system, a unified optical cable online monitoring system management based on Intelligent Cloud software is adopted. The monitoring system is composed of a central server and several distributed hosts. Each distributed host can support the default 32 channel optical fiber link measurement, and can open or close the corresponding measurement ports according to its own test requirements. The monitoring system architecture topology is shown in Figure 4.

4.3. Network transmission
Aiming at the OPGW optical cable online monitoring system of the #1 and #2 transmission lines, the optical transmission system is used to establish a network channel between the substation side terminal and the company's network management side terminal, providing safe, efficient and reliable channel support for data transmission, meeting the channel requirements of the optical cable environment sensing system of the power Internet of things.

4.4. Application positioning
According to the needs of the system, based on the research contents of perception, platform and network, through the online monitoring and management system of optical cable, the operation and
maintenance personnel can carry out online real-time monitoring of optical cable, transmission line environment (fire / galloping / icing) alarm, fault location, network deterioration analysis and other specific application layers to display analysis and early warning functions. Finally, it can realize the dynamic perception of the security situation of the 500 kV transmission line of the power Internet of things, the automatic distribution of early warning information, the intelligent analysis of security threats, and the joint disposal of response measures, so as to improve the ability of prevention and control of the external damage risk and emergency disposal of the 500 kV transmission line.

4.5. System deployment mode
This system consists of the core BOTDR and monitoring system (cloud platform). By BOTDR spontaneous brillouin scattering technology, to monitor whether the power communication cable is attacked by external damage, fire, icing, wind galloping and other risks remotely. The pulse optical signal is injected from one end of the sensing optical fiber, and the Brillouin scattering light generated in the optical fiber is sent back to the photo detector in the opposite direction, and then the Brillouin frequency shift is calculated in the data acquisition and processing system to get the temperature or strain sensed by the sensing optical fiber. The cloud platform monitoring system carries out efficient data transmission, big data deep learning algorithm, and data analysis and processing. Report in time to realize fault location, alarm and early warning, network degradation analysis, etc. The monitoring performance of the system is shown in Table 1 and Table 2.

### Table 1. Performance Parameters.

| Performance                  | Temperature field performance | Stress field performance |
|------------------------------|-------------------------------|--------------------------|
| 1 Measuring range            | -60°C~120°C                   | -                        |
| 2 Temperature resolution     | ±1°C                          | Stress resolution ±10με  |
| 3 Spatial resolution         | 5m                            | Spatial resolution 10m   |
| 4 Space interval             | 0~50km                        | 0~50km                   |

### Table 2. BOTDR Performance.

| Performance                  | Numerical value              |
|------------------------------|------------------------------|
| 1 Dynamic range              | 1310nm ≥45dB 1510nm ≥42dB    |
| 2 Blind area                 | Blind area ≤0.8m Blind area ≤3m |
| 3 Pulse width                | 3~20000ns                    |
| 4 Distance range             | 0.1~400km                    |
| 5 Sampling resolution        | 5cm~12.8m                    |
| 6 Number of sampling points  | Up to 256000                 |
| 7 linear                     | 0.03dB/dB                    |
| 8 Loss threshold             | 0.01dB                       |
| 9 Loss resolution            | 0.001dB                      |

The distributed host can be connected with multiple optical switches to monitor and test the optical fiber lines in the network. The specific network deployment is shown in Figure 5.
5. System application scenario

The main objective of the research is to improve the environmental perception ability of power communication optical cable, realize the reliability, real-time and effectiveness of maintenance, realize the environmental perception of fire, wind disaster, ice disaster along the power communication optical cable, solve the monitoring difficulties of environmental perception and external loss risk of power overhead line, and effectively solve the monitoring problems of power line fire, galloping, icing, etc. The main application directions are as follows:

5.1. Line external damage monitoring

The trip of transmission line caused by the hidden danger of external failure poses a great threat to the safety and stability of power grid. There are many reasons for external failure, such as external mechanical damage, natural disaster damage, artificial damage, chemical corrosion and so on. For sudden natural disasters, it is required to be able to locate in time, facilitate rapid disposal and avoid greater losses. More importantly, for the potential hazards brought by the construction work, if early warning can be given, the cable can be protected from damage. By detecting the physical state of the optical cable, the fault location can be located. Through the built-in BOTDR module, the optical fiber length, loss, fiber breakage and other external damage monitoring based on BOTDR technology, the optical pulse is continuously sent to the optical fiber. Because of the non-uniformity of the optical fiber itself, each point of the optical fiber will produce a backscattered light. The photo detector is used to analyze the backscattered light, and the relationship model between the characteristics of optical signal and the external damage event of optical cable is established to realize the judgment and evaluation of the external damage state of optical cable, and give the early warning information.

5.2. Line galloping risk monitoring

The monitoring system can obtain the length and loss of optical cable directly. The test results of a certain optical cable are shown in Figure 6. The analysis is as follows: firstly, there is an external damage hidden danger event at 20km, which will be recorded by the system, but it does not exceed the warning level set by the administrator, so it will not alarm. Secondly, there is an external damage event at 40km, and the system will give an early warning and positioning information immediately.
The cable in the high altitude is affected by the change of the environmental wind force. When the wind force exceeds a certain value, it will generate natural dancing. Or because of the change of the electric field, the high-altitude cable will dance. The reason of galloping is very complex, and galloping will lead to the change of cable stress field. The main means of line galloping are video monitoring and acceleration sensor monitoring, which are vulnerable to electromagnetic interference and other problems, and there are high damage rate, low accuracy, unreliable data transmission and other conditions[7]. The monitoring system based on BOTDR technology can get the real-time wind status along the cable through real-time and accurate measurement of the stress change of the cable, combined with the stress coefficient of the cable, and then get the risk coefficient of galloping according to the stress coefficient of the power cable. The figure below shows the result of a dance. As shown in Figure 7, there is a dancing level approaching the strong dancing area at 28km. From 40km to 50km, it shows weak galloping characteristics. According to the requirements, we can set a period of time to analyze the dance level of the monitoring area, and display the dance data at two different time points.

Figure 7. Dance Monitor Graph.

5.3. Risk monitoring of line icing
Using distributed optical fiber sensor to monitor icing can improve the ability of power grid to resist icing disaster [8]. Icing climate is the direct cause of line fault [12]. After the icing, the stress field and temperature field of the redundant optical fiber in the transmission line change. By establishing the relationship between the optical parameters and the stress physical quantity and the temperature field of the optical cable, monitoring the temperature field and the stress field of the optical cable at each point along the line, and providing the ice cover thickness, ice cover section and other ice cover status information. In order to obtain the temperature field and stress field along the optical cable, the technology of BOTDR is used to monitor the icing state of the transmission line.

Figure 8 shows the figure of icing monitoring. It shows that there are three icing areas in this section of monitoring cable. Area a has a large ice coverage range and a strong level; most of area B has ice coverage; part of area C has ice coverage.

Figure 8. Icing Monitor Pattern.

5.4. Line fire risk monitoring
The optical fiber temperature measurement module can monitor the whole optical fiber, and sense the change of the measured temperature with the length of the optical fiber in the form of a continuous function of distance. Optical fiber is both transmission and sensing medium. At the same time, it also has the advantages of anti electromagnetic interference, anti combustion, small size, small impact on the measured temperature field and other incomparable advantages of other sensors[9]. The
temperature field and stress field along the cable can be accurately obtained by BOTDR, and the abnormal temperature change at any point along the cable can be monitored, so as to know the fire risk. As shown in Figure 9, it is a schematic diagram of fire monitoring. When the local temperature reaches the warning value, the system will give an alarm automatically. Users can quickly find the warning area through GIS map.

Figure 9. Fire Monitori Graph.

6. Conclusion
Through the research and application of on-line monitoring of OPGW cable in 500kv #1 and #2 transmission lines, this paper realizes on-line monitoring of temperature field and stress field in the spare core of OPGW cable in transmission lines, implements the intelligent sensing means of preventing external damage, fire, icing and dancing, and monitors the important environmental parameters of the cable line in real time with the help of large data technology, it achieves the purpose of external damage detection, optical cable fault operation and maintenance intelligent management. At the same time, it enhances the ability of resisting various natural disasters and external damage of optical cable and transmission line on the same tower and the ability of resource allocation, which can effectively enhance the reliability of backbone communication optical cable, realize the rapid operation and maintenance management, and meet the information communication needs of various links and different fields of power grid development. It helps to build a power communication network with advanced technology, good practicability, full coverage and strong resistance.

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