Ice thickness estimation method of overhead line based on distributed optical fiber temperature sensing

Xiaoming Zou¹, Xinzhan Liu¹, Yi He¹, Yingbin Lan¹, Liuhui Yang¹ and Lijuan Zhao²,³

¹Heyuan Power Supply Bureau, Guangdong Power Grid Corporation, Heyuan 517000, China
²Department of Electronic and Communication Engineering, North China Electric Power University, Baoding 071003, China
³E-mail: hdzlj@126.com

Abstract. In order to monitor icing condition of overhead line based on distributed optical fiber temperature sensing, the transient temperature field models of radial and axial heat transfer for iced overhead line are constructed. The finite element method is used to solve the models to obtain the axial and radial temperature distribution inside the overhead line. Based on the two models, the change of the optical fiber temperature with time when the ambient temperature changes at a certain rate is investigated. At the same time, the change of optical fiber temperature with time in the iced and uniced sections under different ice thicknesses is also investigated. On this basis, the change of temperature difference with time is investigated. The formula of ice thickness estimation according to the temperature difference between iced and uniced sections’ optical fibers is obtained. This work lays a foundation for the evaluation of ice condition of overhead line based on distributed optical fiber temperature sensing.

1. Introduction

As an important part of the transmission and distribution system, the high-voltage overhead line is long and is subjected to different kinds of stress. It is inevitable to suffer from lightning strike [1], icing [2], mountain fire [3] and external damage [4] during operation, and sometimes even lead to an interruption of the power supply to customer. Icing is a common threat to overhead lines, which not only causes flashover, but even leads to tower collapsing. How to evaluate the state of icing and avoid the occurrence of faults is of great value to improve the reliability of power supply.

At present, overhead line icing monitoring methods mainly include the weighting method [5], the video surveillance method [6], the tilt angle method [7], and the fiber Bragg grating method [8], etc. These monitoring methods have made contributions to ensuring the normal operation of overhead lines and avoiding accidents. However, these methods still have some weaknesses, such as poor anti-interference ability, short lifetime, poor reliability of data transmission, and difficulty in monitoring the state of the whole overhead line. Therefore, the problem of overhead line icing monitoring needs to be further investigated. Because there are some optical fibers deployed into OPGW (Optical Fiber Composite Overhead Ground Wire) [9] and OPPC (Optical Phase Conductor), the temperature or strain along the optical fiber can be easily measured based on BOTDR (Brillouin Optical Time Domain Reflectometer) [10] or ROTDR (Raman Optical Time Domain Reflectometry) [11]. The optical fiber strain may be different between the iced section and the uniced section [12-13]. The icing
state of the overhead line can be estimated based on it. However, the estimation method about ice thickness based on distributed optical fiber temperature sensing simply goes unreported.

In order to solve this problem, the transient temperature field models of radial and axial heat transfer of the iced overhead line are constructed. The axial and radial temperature field distributions of the overhead line are obtained by solving the model using the finite element method. Based on the two models, the change of the optical fiber temperature with time when the ambient temperature changes at a certain rate is investigated. At the same time, the change of optical fiber temperature with time in the iced and uniced sections under different ice thicknesses is also investigated. On this basis, the change of temperature difference with time is investigated. The estimation formula of ice thickness based on the temperature difference between the iced and uniced sections' optical fibers is obtained.

2. Temperature field model of iced overhead line

2.1. Modeling

The OPGW (model OPGW-24B1-145) is studied in this work. It contains an optical unit in which 24 G.652 optical fibers are contained. In order to moderately simplify the model, the axial and radial two-dimensional temperature field models of iced OPGW are constructed in this section. Since OPGW does not produce heat, in the model, air, OPGW and ice layer are considered to transfer heat through convection and radiation. The radial heat transfer model is constructed according to the cross-section of OPGW-24B1-145, and an approximately circular ring region is used to simulate the ice layer. According to the heat transfer principle, the outer surface of the iced layer is the interface between ice and air, which corresponds to the convective heat transfer boundary and conforms to the third boundary condition. The material parameters used in the model are presented in Table 1. The thickness of ice layer is 4 mm. The constructed radial heat transfer model and the corresponding meshed one are shown in Figure 1. Note that in order to improve the accuracy of the calculation results, the extremely fine element size is used in meshing. The number of elements is 44019.

| Component                      | Material             | Heat capacity at constant pressure/J/(kg·K) | Density/kg/m³ | Heat conductivity coefficient/W/(m·K) |
|--------------------------------|----------------------|-------------------------------------------|---------------|---------------------------------------|
| Radial heat transfer           |                      |                                           |               |                                       |
| Aluminium-conductor            | Aluminum             | 900                                       | 2700          | 238                                   |
| Steel-reinforced cable         | Steel                | 475                                       | 7850          | 44.5                                  |
| Optical unit                   |                      |                                           |               |                                       |
| Stainless steel                |                      | 512                                       | 7850          | 48                                    |
| Fiber filling ointment         |                      | 2500                                      | 900           | 0.12                                  |
| Optical fiber                  |                      | 1000                                      | 2300          | 12                                    |
| Axial heat transfer            |                      |                                           |               |                                       |
| Line                           |                      | 670                                       | 6850          | 100                                   |
| Ice                            | Ice                  | 2100                                      | 920           | 2.22                                  |

The physical field and boundary conditions of the axial heat transfer modeling are the same as those of the radial heat transfer model. Since the cross-section size of OPGW is significantly lower than its length, it is simplified as a cylinder with equal radius in modeling, and two-dimensional axial symmetry is adopted for modeling. The length of the OPGW in the model is 7.5 m, and ice covers on the OPGW in two intervals of 1.5 m ~ 3 m and 4.5 m ~ 6 m. The schematic diagram is displayed in Figure 2. The thickness of ice layer is 4 mm. The material parameters used in the model are also listed in Table 1. The partial axial heat transfer model and the meshed one are shown in Figure 3. The number of elements is 6510.
2.2. Results
The initial ambient temperature is set to 0°C, and the ambient temperature decreases at a rate of 2°C/h. The temperature distributions of OPGW within 0~10 h are investigated. The radial and axial heat transfer models are calculated by the finite element method, and their temperature distributions at the 10th h are depicted in Figure 4 and Figure 5, respectively. Figures 4 and 5 show that the temperature of
OPGW gradually decreases from the inside to the surface because the ambient temperature is lower than the OPGW temperature. In addition, ice layer affects heat transfer, therefore the OPGW temperature in the iced section is higher than that in the uniced section in Figure 5. In addition, the calculation results of the radial heat transfer model are slightly different from the results of the axial heat transfer model. This is mainly due to the fact that the structure and material parameters of the two models are not completely same.

![Figure 4. Calculated temperature distribution for radial heat transfer model.](image1)

![Figure 5. Calculated temperature distribution for axial heat transfer model.](image2)

3. Estimation of ice layer thickness based on temperature difference

Based on the radial heat transfer model established in Section 2, the OPGW temperature distribution is calculated when the ice thickness varies in the range of 1-10 mm and the step size is 1 mm. Change of the optical fiber temperature with time under different ice thicknesses is obtained, as shown in Figure 6. It can be seen from Figure 6 that the optical fiber temperature gradually decreases with the increase of time, which is consistent with the fact that the ambient temperature decreases with the increase of time. In addition, the optical fiber temperature increases with the increase of ice thickness. This is because the thicker ice layer can more effectively prevent the OPGW from transferring heat with the surrounding air.
Based on the axial heat transfer model constructed in Section 2, change of the optical fiber temperature in iced section and noniced section with time under different ice thicknesses is displayed in Figure 7. By comparing Figure 6 and Figure 7(a), it can be seen that the influence of the ambient temperature and ice thickness on optical fiber temperature is similar for the two heat transfer models. This validates the results to a certain extent. By comparing Figure 7(a) and Figure 7(b), it can be seen that the optical fiber temperature is different between the iced section and the noniced section, and the temperature difference between the two sections is related to the ice thickness. This is because the ice layer affects the heat transfer process. Figure 8(a) shows the relationship between the temperature difference and the ice thickness at different times. Obviously, the thicker the ice layer is, the greater the temperature difference between the two sections is. When the time is 10 h, the relationship between the temperature difference and the ice thickness is depicted in Figure 8(b). Considering the curve, the ice thickness can be represented as follows.

\[ d = a \Delta T^2 + b \Delta T + c \]  \hspace{1cm} (1)

where \( \Delta T \) is the temperature difference in the optical fiber between the iced and uniced sections, °C; \( d \) is ice thickness, mm; \( a, b, \) and \( c \) are coefficients. The fitted formula is shown in Equation (2), and the corresponding curve and error are also drawn in Figure 8(b).

\[ d = -3.13 \Delta T^2 + 12.30 \Delta T + 0.84 \]  \hspace{1cm} (2)
According to the optical fiber temperature measured by BOTDR, ROTDR or BOTDA (Brillouin Optical Time Domain Analysis), the temperature difference can be calculated. Then the ice thickness can be estimated according to Equation (2).

4. Conclusions
In this paper, icing condition evaluation about overhead line based on the distributed optical fiber temperature sensing method is investigated. The transient temperature field models of radial and axial heat transfer of the iced overhead line are constructed. Based on the two models, the temperature distributions for iced overhead line are presented. The change of the optical fiber temperature with time when the ambient temperature changes at a certain rate is investigated. At the same time, the change of optical fiber temperature with time in the iced and uniced sections under different ice thicknesses is also investigated. On this basis, the change of temperature difference with time is investigated. The formula of ice thickness estimation according to the temperature difference between iced and uniced sections' optical fibers is obtained. This work provides a good reference for the ice thickness prediction of overhead lines based on BOTDR or ROTDR.

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References
[1] Sun J, Jiao Z, Zhu X, Yao X and Chen J 2021 Experimental and simulation study of damage mode and influencing factors of lightning damage to optical fiber ground wires under lightning impulse and continuous current High Voltage Engineering 47(5) 1872-1880
[2] Jiang X, Han X, Hu Y and Yang Z 2018 The study of dynamic wet-growth icing model of insulator Proceedings of the CSEE 38(8) 2496-2503+2559
[3] Zhang L, Li X and Zhao W 2019 Simulation analysis of temperature field of optical fiber composite overhead ground wire Electric Power 52(10) 100-107
[4] Liang Z, Zhang X and Wei M 2011 Power communication cable maintenance and external damage prevention measures Telecommunications for Electric Power System 32(6) 67-72
[5] Wang K, Sun X, Sheng G, Xu W, Liu Y and Jiang X 2014 Error comparison among three online monitoring methods of conductor sag of overhead transmission line High Voltage Apparatus 50(4) 27-34
[6] Liu Z, Miao X, Chen J and Jiang H 2020 Review of visible image intelligent processing for
transmission line inspection *Power System Technology* **44**(3) 1057-1069

[7] Hu Q, Yu H, Xu X, Shu L, Jiang X, Qiu G and Li H 2016 Study on torsion characteristic and equivalent ice thickness of bundle conductors *Power System Technology* **40**(11) 3615-3620

[8] Wei J, Hao Y, Fu Y, Yang L, Gan J and Li H 2020 Experimental study on glaze icing detection of 110 kV composite insulators using fiber Bragg gratings *Sensors* **20**(7) 1834

[9] Wu N, Wang H, Zhang Z, Guo W, Lu E and Zhou Z 2017 Research of transmission line icing wide-area monitoring based on OPGW *Electric Power* **50**(5) 65-70

[10] Hao Y Q, Cao Y L, Ye Q, Cai H W and Qu R H 2015 On-line temperature monitoring in power transmission lines based on Brillouin optical time domain reflectometry *Optik-International Journal for Light and Electron Optics* **126**(19) 2180-2183

[11] Laarossi I, Quintela-Incera M Á and López-Higuera J M 2019 Comparative experimental study of a high-temperature Raman-based distributed optical fiber sensor with different special fibers *Sensors* **19**(3) 574

[12] Zhang W, Wu R and Qin W 2016 Icing load monitoring of OPGW based on strain analysis *Southern Power System Technology* **10**(11) 52-58

[13] Yang K, Hao Y, Ye Q, Cai H and Qu R 2018 Ice-coating monitoring research on aerial cables with BOTDR sensing system *Laser Journal* **39**(8) 43-45