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The Mechanical Model of Overhead Transmission Lines and A Novel Iteration Algorithm for the Icing Monitoring via Fiber Optic Sensors[1]

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***Abstract*— Icing on overhead transmission lines is a great threat to the operation security of power systems. In China, since the 2008 snow and ice storm which leaded to 1.52 billion U.S dollar losses, icing monitoring technology research became a hot point. Fiber optic sensor, because of its obvious advantages of no electromagnetic interference, safety and no power supply, is a very active in overhead transmission line icing monitoring field. In this paper, a novel iteration algorithm is brought out to solve the ice thickness calculation problem with the fiber Gragg grating (FBG) sensors' measurement stress and temperature data. The mechanical model of overhead transmission lines is presented firstly and then the iteration algorithm is given in detail. A simulation test proves the effectiveness of the algorithm.**

***Index Terms*—Icing Monitoring; Fiber Bragg Grating; Transmission Line; Iteration algorithm.**

I. Introduction

ICING on the overhead transmission lines may lead to severe accidents, such as mechanical overload of conductor, tower failure, insulator string's icing & flashover, conductor galloping, etc. Anyone of these accidents is the vast potential threat to the security operation of the power system. For example, from January to February in 2008, snow and ice storms attacked the southern of China. Thousands kilometers of transmission lines were iced. In some segments, the thickness of the ice coating was up to 80~100mm, which obviously exceeded the design value. Some provincial grid were destroyed because of the 500kV transmission line trips. The whole direct economic loss was reached 1.52 billion U.S dollar in this disaster [1]. But with continuous increasing power demand to support the Chinese economic development, more and more high voltage transmission lines have to pass through the areas with atrocious weather conditions. Therefore, the need to secure the transmission grid motivates the research concerned with icing monitoring and de-icing technology in China.

Until now, there are four kinds of transmission line icing monitoring method [2-4]. The earliest method was the use of icing observation station, which was used 50 or 60 years ago to monitor the conductor icing manually. This method can acquire the first-hand icing information but with the cost of high expense, which limits its spread. Photograph or video method which developed in these ten years

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also monitors the lines icing situation directly. But in the application process, the camera lens maybe covers with the ice or dust. This brings out a great difficulty to distinguish the icing on the transmission lines. The third method, which measures the force upon the insulator string through the weight sensors, is widely used all over the world. And the fourth method, just like the third one but with more intuition, measures the strain of the transmission lines directly via the strain sensors. Whether the strain sensor or the weight sensor, they can be classified into two kinds: traditional electric quantity sensor, and fiber-optic sensor. Compared with the widely used electric quantity sensor, fiber-optic sensor has some attractive advantages, such as long distance monitoring due to low transmission loss, immunity to the electromagnetism disturbance. In these ten years, the fiber-optic sensor utilization in monitoring the power facilities, such as the temperature of 400kV power transmission lines[5], the aeolian vibrations of the 60kV power lines[6], and the icing on the transmission lines[7] are developed very quickly. The basic principle and fixing method of Fiber Bragg Grating (FBG) sensor, and experimental results are described in detail in the previous research [7-10]. In this work, we propose a novel iteration algorithm to solve the icing thickness calculation problem. We first introduce the mechanical model of the iced transmission lines, and then present the iterative algorithm. And in the last part of this paper, we bring out the experimental results to investigate the effectiveness of the iteration method.

II. Mechanical Model of the Overheard Transmission Lines

An overhead transmission lines can be described mathematically by the well-known parabolic formula [11]:

$$\sigma_x = \frac{\sigma_0}{\cos\beta} + \frac{r^2(l-2x)^2}{8\sigma_0\cos\beta} - \frac{r(l-2x)}{2}tg\beta \tag{1}$$

where σ_x is the axial stress at the horizontal position x of the transmission lines , σ_0 is the horizontal stress on the lowest position, β is the angle of the height difference, l is the span length, and r is the conductor mass-length-area ratio (if icing, the ice mass also included). Fig. 1 shows the mechanical model of overhead transmission line.

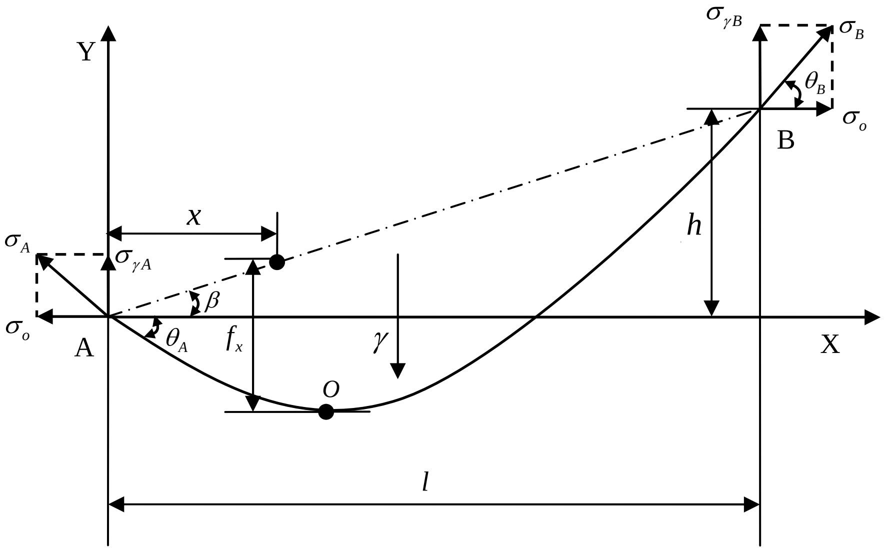

Fig. 1 **Transmission line mechanical analysis**

Then the static strain of the conductor can be found from:

$$\varepsilon_x = \frac{\sigma_x}{EA} = \frac{1}{EA}[\frac{\sigma_0}{\cos\beta} + \frac{r^2(l-2x)^2}{8\sigma_0\cos\beta} - \frac{r(l-2x)}{2}tg\beta] = f(\sigma_0, r, x) \qquad (2)$$

where EA is the product of the elastic modulus of the conductor and its cross-sectional area. In the Eq. 2, after the strain sensor is fixed on the conductor, the variable x is a known number. So the strain ε_x is the function of r and σ_0. When the ice mass on the transmission lines changed, the r value and the stress of the conductor are modified accordingly. The FBG sensor wavelength is shifted to reflect this change. Based on this phenomenon, we can develop the FBG icing monitoring apparatus.

Obviously, the power conductor should be fixed firstly and therefore it brings out the possibility to bind the FBG strain sensors on itself. So, before the FBG strain sensors begin to work, there already lies strain acting on the conductor. FBG strain sensor's measurement, denoted by $\Delta\varepsilon_x$, is the stress increment and it can be induced by not only the environment loads but also the temperature variety. In order to distinguish from the influence of the temperature, the icing monitoring system should measure the conductor temperature near the strain sensor. This also can be realized through the FBG temperature sensor. Eq. 3 describes the strain increment induced by the temperature:

$$\Delta\varepsilon_{tx} = a(t - t_0) \qquad (3)$$

where a is thermal expansion coefficient of the conductor, t is the conductor current temperature, and t_0 is the initial temperature of the transmission line at that time when it was fixed on the insulator. Therefore the strain increment generated by the ice mass can be measured by the FBG strain sensor and temperature sensor, and can be denoted as following:

$$\Delta\varepsilon_{Tx} = \Delta\varepsilon_{x} - \Delta\varepsilon_{tx} \tag{4}$$

$\Delta\varepsilon_{Tx}$ is the value measured by the FBG strain sensor and reflects the mechanical status on the transmission lines.

III. Iteration Algorithm to Calculate Ice Mass

In the Eq. 2, we find that there lies two variables r , σ_0 and we have only one measured value $\Delta\varepsilon_{Tx}$. So, we present an iteration algorithm to calculate the ice mass using the following steps:

Step 1) Calculate the length and the average stress of the conductor without ice using

$$L_1 = \frac{l}{\cos\beta} + \frac{r^2 l^3 \cos\beta}{24\sigma_0^2} \tag{5}$$

$$\sigma_{av1} = \frac{\sigma_0}{2L_1}[l + \frac{L_1^2 + h^2}{\sqrt{L_1^2 - h^2}} ch \frac{rl}{2\sigma_0}] \tag{6}$$

where, the means of l , β , σ_0 is just the same as Eq. 1, h is the height difference between the two ends. And the initial values of r , σ_0 are saved as $r^{'}$, $\sigma_0^{'}$.

Step 2) The ice thickness b and the lowest position horizontal stress σ_0 are assumed. For the first iteration, b is equal to zero, and σ_0 is the initial value at the time when the conductor was fixed on the insulator.

Step 3) Calculate the new conductor mass-length ration r :

$$r = \frac{mg + \rho_{ice}\pi b(b+D)g}{A} \tag{7}$$

where,

m the conductor mass per unit length;

g gravity, 9.8m/s^2 ;

ρ_{ice} the density of the ice, $0.9\times10^{-3}\text{kg/cm}^3$;

D the conductor diameter;

A the conductor cross-sectional area

Step 4) The elongated length and the average stress of the conductor with ice are calculated using

$$L_2 = \frac{l}{\cos\beta} + \frac{r^2 l^3 \cos\beta}{24\sigma_0^2} \tag{8}$$

$$\sigma_{av2} = \frac{\sigma_0}{2L_2}[l + \frac{L_2^2 + h^2}{\sqrt{L_2^2 - h^2}} ch \frac{rl}{2\sigma_0}] \tag{9}$$

Step5) Based the σ_{av2} value, calculate the icing conductor length again using the transmission line state equation:

$$L_2^{'} = L_1 \frac{[1 - \frac{\sigma_{av1}}{E}]}{[1 - \frac{\sigma_{av2}}{E}]} \tag{10}$$

Step 6) Calculate the difference between $L_2^{'}$ and L_2. If the absolute value of the conductor length difference is less than a specific value Δ_1, for example, $\Delta_1 = 0.001m$, go to step 7. Else calculate the horizontal stress σ_0 of the lowest position using following formula, then go to step 4:

$$\sigma_0 = \sqrt{\frac{r^2 l^3 \cos\beta}{24(L_2^{'} - \frac{l}{\cos\beta})}} \tag{11}$$

Step 7) Then the strain increment $\Delta\varepsilon_{TX}^{'}$ with the ice thickness b can be calculated using the formula 12.

$$E \times \Delta\varepsilon_{TX}^{'} = \frac{\sigma_0 - \sigma_0^{'}}{\cos\beta} + \frac{(l-2x)^2}{8\cos\beta}(\frac{r^2}{\sigma_0} - \frac{r^{'2}}{\sigma_0^{'}}) + \frac{(r - r^{'})(l-2x)}{2} tg\beta] \tag{12}$$

Step 8) Compare this calculated value $\Delta\varepsilon_{TX}^{'}$ with the actual measured value $\Delta\varepsilon_{Tx}$. If the absolute difference of these two strains is less than a specific value Δ_2, then output the ice thickness b. Else, the ice thickness b is increased or decreased and the steps are continued until absolute difference is less than Δ_2.

IV. Simulation Experiment

Here, a simulation experiment is designed to investigate the effectiveness of the algorithm. Some parameters and initial state are listed as following: E=65000N/mm^2, A=425.24mm^2, l=1000m, D=26.82mm, h=0, r=0.03111, σ_0 =58.29 N/mm^2, $a = 20.5 \times 10^{-6} m/^{\circ}C$, t_0=15℃.

If the FBG strain & temperature sensors are placed at the position $x = 10$ m, the strain and temperature value at this point are 55.5℃ and 1460 $\mu\varepsilon$. At the iteration beginning, we assume that the ice thickness b=0 and σ_0 is the same as the initiate states. After 147 iteration calculation, the value of the ice thickness and the horizontal stress are obtained. They are 10.08 mm and 126.7N/mm^2 respectively. Fig. 2 shows the change of the calculation b and σ_0 in the calculation process.

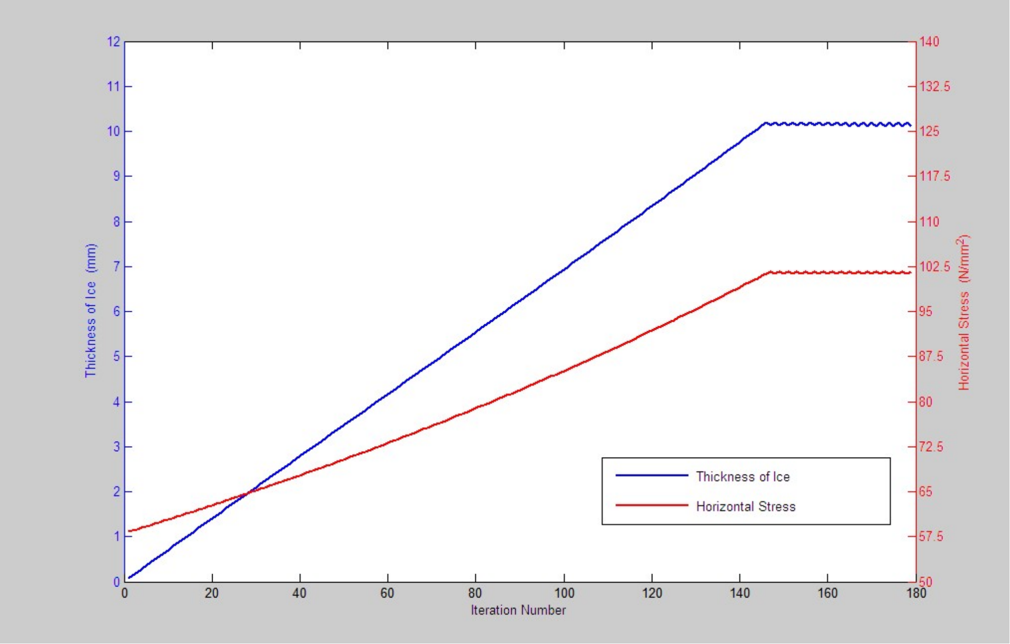

Fig. 2 Ice thickness and horizontal stress changed with iteration process

V. Conclusion and Future Works

Although the icing monitoring technology are developed for a very long time, but in the application case, they meet the great challenge from the acute environment conditions, continuous power supply, high reliability and low maintenance cost for the long-time work. The fiber optic technology shows its potential in the transmission lines icing monitoring.

In this paper, we first present the mechanical model of the transmission lines and then bring out a novel iteration algorithm for the icing thickness calculation based on the strain and temperature data which obtained by the FBG sensors. The simulation experiment proves its validity. Future work should be focused on data processing of FBG signal to deal with the more complex situation, such as the measurement noise and the effect of the wind.

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VII. Biographies

Cao Yongxing was born in Sichuan Province, P.R. China, in 1963. He is a senior engineer and the director of the department of power system security & operation at Sichuan Electric Power Research Institute. His current research interest includes high voltage engineering and security of power transmission systems.

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