Model updating approach for icing forecast of transmission lines by using particle swarm optimization

Haigang Tian¹, *, Naifeng Liang², Puzhi Zhao³, Xuan Wang³, Chuangwei Zhu³, Sanchun Zhang¹, Wei Wang¹

¹State Grid Xin Jiang Economic Research Institute, Urumqi 830000, China
²State Grid Xin Jiang Electric Power Company, Urumqi 830000, China
³State Grid Xin Jiang Yi Li Electric Power Company, Urumqi 835000, China

*Corresponding author e-mail: axl6533503@163.com

Abstract. With the purpose of predicting icing of transmission lines, a model updating approach is presented in this study. The changes of structural dynamic response of transmission lines that is caused by icing is studied firstly by using finite element method. Then, model updating method and particle swarm optimization is implemented to indentify the thickness of icing according to the alternation of natural frequencies. The results show that the proposed methodology is meaningful to monitor line icing.

1. Introduction
Icing of transmission lines would cause line gallopping, insulator flashover and even tower collapse which is a great threat for the operation of power grid [1-2]. Thus, effective monitoring and condition assessment of line icing is the key issue which needs to be solved, and the establishment of icing forecast plays an important role in the operation of power grid.

It’s very difficult to evaluate the condition of lines manually considering that transmission lines are located sparsely. Hence, the on-line monitoring technique has attracted increasing attentions in engineering application. The current monitoring strategy are mainly based on measuring the weight, angle of insulator, wind speed, temperature and humidity. The equivalent thickness of line icing can be estimated according to measured data [3-5], based on that, related staff will be alerted as long as the thickness evaluated beyond a predefined value. However, the actual icing condition is usually distributed non-uniformly along the length of line, thus, the monitoring technique based on the evaluation of equivalent thickness is unable to get more information of icing distribution in details. In this work, a methodology for icing forecasting based on model updating method is presented. The modal frequencies are introduced to identify the icing condition of transmission lines with the help of artificial intelligence technique, and the results show that the proposed approach is able to identify and predict the distribution of icing.

2. Identification of icing based on model updating process

2.1. Numerical model of transmission lines
Transmission line is one kind of cable-suspended structure which cannot bear compressive force and flexural moment, and a large deformation would be generated when load is applied. In this study,
ANSYS, a commercial FE (finite element) method software is implemented to establish numerical model, and the transmission line can be modeled appropriately by using LINK10 element according to its mechanical characteristics.

The FE analysis of transmission line is a typical geometrical non-linearity problem. It is very important to obtain the geometric shape under load (including gravity), and the solution of each load step highly depends on the results in the previous one. Therefore, to complete the process of shape finding, the initial FE model should be established based on catenary theory. Then, the FE model needs to be updated as long as gravity is introduced, and the converged results is the real FE model of transmission line.

2.2. Model updating method
Due to the uncertainties in simplifying assumptions of structural geometry, material properties and boundary conditions, there is always a difference between FE analysis and experimental test. The propose of model updating method is to adjust numerical model with experimental results which are considered to be accurate, thus, a more realistic FE model can be achieved and the unknown structural parameters and conditions can be identified according to the process which behaves as an inverse problem [6]. Dynamic responses, such as natural frequencies and modal shapes, are able to reflect the structural properties and are widely used for model updating method [7-8], hence, it will be introduced with the purpose of identifying icing in this study. A flowchart of model updating procedure is illustrated in Fig 1.

![Figure 1. Flowchart of model updating method](image)

2.3. Icing forecasting based on model updating method
The selection of parameter for updating is a key problem for model updating process which needs to be sensitive enough to structural response and changing of structural parameters. For transmission line, icing would increase structural mass leading to the alternation of dynamic behaviors, and conversely structural dynamic measurements are able to reflect the icing conditions. Therefore, the thickness of icing is chosen as the updating parameter in this study, and it will be transferred to the mass of each element in order to carry out the FE analysis and model updating procedure.
Figure 2. The area of transmission line with icing

As shown in Fig 2, the radii of line is \( r_{\text{line}} \), the equivalent thickness of icing is \( r_{\text{ice}} \), with the purpose of simplifying model updating process, the equivalent area of line \( A_{\text{eq}} \) is introduced herein as the updating parameter as shown in Eq. 1

\[
A_{\text{eq}} = A_{\text{line}} + \frac{\rho_{\text{ice}}}{\rho_{\text{line}}} \times A_{\text{ice}}
\]  

(1)

where \( A_{\text{ice}}, A_{\text{line}} \) and \( \rho_{\text{ice}}, \rho_{\text{line}} \) represent the area and density of icing and transmission line, where the icing area is

\[
A_{\text{ice}} = \pi \left[ (r_{\text{line}} + r_{\text{ice}})^2 - r_{\text{line}}^2 \right]
\]  

(2)

Until now, the changing of structural mass caused by icing is transferred to equivalent area of transmission line by using Eqs. (1)-(2), and the model updating process can be completed by updating the area of each element in FE model.

Furthermore, single objective optimization is the widely used approach in model updating procedure, and the formation of objective function predominates the final results. Dynamic response (such as natural frequencies, modal shapes, frequency response function e.g.) are usually selected to construct objective functions [8], hence, the objective function \( F \) applied in this study is shown as follows

\[
F = 1 - MAC = 1 - \frac{|f_a^T f_t|^2}{(f_a^T f_a)(f_t^T f_t)}
\]  

(3)

where \( f_a \) and \( f_t \) denote the vector constructed by natural frequencies which are obtained by numerical analysis and experimental test, respectively. MAC represents modal assurance criteria, whose value equals 1 if \( f_a \) and \( f_t \) correspond perfectly and it equals 0 conversely.

2.4. Optimization algorithm for model updating

As presented previously, the identification of line icing has been transferred to an optimization problem which needs to minimize the objective function in Eq. (1), besides, the optimization algorithm plays an important role in model updating procedure. With the development of artificial intelligence, some evolutionary algorithms are implemented in this field, such as particle swarm optimization (PSO). PSO performs quite well in global searching in comparison of conventional optimization methodology,
besides, the advantages of fast convergence and easy programming makes it become promising in optimization and model updating [9-10].

As an evolutionary optimization approach, PSO starts searching optimal solution in the entire space in the following way

\[ v_{i}^{k+1} = w \cdot v_{i}^{k} + c_1 \cdot r_1 \cdot (p_{best, i} - x_{i}^{k}) + c_2 \cdot r_2 \cdot (g_{best} - x_{i}^{k}) \]  

(4)

\[ x_{i}^{k+1} = x_{i}^{k} + v_{i}^{k+1} \]  

(5)

where \( x_{i}^{k} \), \( v_{i}^{k} \) denote the location and velocity of \( i \)-th particle in \( k \)-th iteration, \( c_1 \) and \( c_2 \) are the constant related to convergence of swarm which usually equals 2. \( r_1 \) and \( r_2 \) are random number between 0 and 1 in order to avoid falling into local optimum, and \( w \) denotes the inertial item that controls the velocity of swarm.

With the purpose of identify icing condition and distribution along transmission line in this work, the equivalent thickness of icing in each element \( r_{ice}^{j} \) are used to construct updated vector \( \vec{r} = (r_{ice}^{1}, r_{ice}^{2}, \ldots, r_{ice}^{n}) \), and PSO is implemented based on experimental test data. The procedure is illustrated in Fig 3 as follows.

Figure 3. The flowchart of identification of line icing

3. Case study
To evaluate the accuracy and efficiency of proposed approach, a case study is carried out for a transmission line with geometrical and material properties as shown in Tab 1.

| Table 1. Geometrical and material properties of transmission line |
|---------------------------------------------------------------|
| Span (m)          | 435          |
| Area (mm²)        | 275.96       |
| Elastic modulus (MPa) | 73000   |
| Mass (kg/km)      | 922.2        |
| Fracture force (N)   | 75620       |
First of all, FE model is constructed based on ANSYS, and initial strain and gravity are applied to employ the shape finding process by updating structural geometrical location. Then, the natural frequencies can be obtained as shown in Tab 2.

| Natural frequencies | (Hz) |
|---------------------|------|
| \( f_1 \) (out-of-plane symmetrical) | 0.3283 |
| \( f_2 \) (in-plane symmetrical) | 0.3381 |
| \( f_3 \) (in-plane anti-symmetrical) | 0.6575 |
| \( f_4 \) (out-of-plane anti-symmetrical) | 0.6577 |
| \( f_5 \) (out-of-plane symmetrical) | 0.9887 |
| \( f_6 \) (in-plane symmetrical) | 0.9890 |

The structural changing caused by icing would lead to alternation of dynamic behaviors. In order to evaluate the influences of different thickness of icing on natural frequencies, three cases are assumed: the line is divided into six parts uniformly, three icing conditions with thickness of 5, 8, 10 mm are applied on the third part, respectively. Then, the thickness of icing is transferred to equivalent area of line by using Eqs. (1)-(2), and the first six natural frequencies are calculated under the three cases. The effect of icing thickness on changes of modal frequencies is illustrated in Fig. 4.

![Figure 4. Influences of icing thickness on changes of natural frequencies](image)

It is clear in Fig. 4 that the changing of natural frequencies increases with the increasing of icing thickness, and natural frequencies has the capability to reflect the alternation of icing which demonstrates that frequencies are sensitive enough to form objective function for model updating process. To verify proposed approach for the identification of icing, the transmission line with 10mm thickness of icing is chosen as a benchmark, and the natural frequencies are calculated as pseudo experimental data \( f_i \) to construct objective function as shown in Eq. (3). The thickness of icing \( r_{ice} \) is transferred to equivalent area of line \( A_{eq} \), and the vector \( \vec{r} \) which is formed by the thickness of icing in each element \( r_{ice} \) will be updated by employing PSO algorithm to minimize objective function in Eq (3). The results of identification is shown in Fig 5.
From the results it can be seen that icing is located at the middle span of line which correspond quite well with predicted values. Thus, based on the changing of natural frequencies it is able to identify line icing by using proposed model updating approach and PSO algorithm. Compared with conventional strategy of icing detection based on static measuring, the presented method focuses more on the distribution of icing along the length of transmission line.

4. Conclusion
With the purpose of identify icing of transmission line, the thickness of icing is transferred into equivalent area of line in this study, and modal frequencies are selected to form objective function in order to carry out model updating process. The results show that modal frequencies are sensitive enough to reflect structural alternation. Besides, as an evolutionary algorithm, PSO is effective in searching optimum solution for the identification of icing. In this work, more attentions were paid to the distribution of icing along the length of power line rather than global equivalent thickness of icing. Furthermore, it should be noticed that symmetrical changing in symmetrical structure would cause same variations for structural responses, thus, more dynamic information (modal shapes e.g.) should be introduced to increase accuracy.

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