Reliability Analysis and Safety Improvement Measures Research of Transmission Line Tower-Line Structure under Ice-Wind Conditions

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Abstract. The tower-line structure system of transmission line is a whole composed of tower structure, insulator, fittings and grounding wire and other components or subsystems. Its reliable operation is of great significance to the safe and stable operation of power system. In this paper, the reliability analysis method of transmission line tower-line structure system under the combination of ice and wind is modeled. Firstly, the reliability index of pole-tower structure, insulator, fittings and grounding wire is calculated by checking point method of first-order second-moment method. Then, the reliability calculation method of series structure system is used to calculate pole-tower structure, insulator, fittings and grounding wire. Finally, taking a straight tower and tension tower as examples, the system reliability indices of pole-tower structure, insulator, fittings and ground wire under ice-wind combination are calculated and analyzed, which can provide reference and guidance for disaster prevention of transmission lines.

1. Introduction
Transmission lines are affected by climate, topography and other conditions, and freezing disasters often occur [1-2]. In the case of icing, the over-stress will lead to failure of the more fragile element if the stress of each element exceeds the design value. In the case of strong winds, line galloping will lead to broken guide wires, damaged poles and towers, and dropped metal tools, etc., seriously affecting the stable operation of the transmission lines [3-4]. Therefore, it is necessary to analyze the reliability of transmission line tower structure system in combination of ice and wind to reduce transmission line failures. The reliability of each part directly affects the reliability of the whole tower structure system [5]. At present, there are many researchers studying on the reliability of tower components at home and abroad, but there are few researches on the reliability of tower line structure system. Reliability analysis for failure modes of single structural members mainly includes first-order second-moment method, Monte-Carlo simulation method, random finite element method [6-8], etc. This paper applied a second order moment method of the checking point method, the combination of ice wind tower, under the condition of insulator, hardware, conducting ground components reliability was analyzed, and according to the results put forward the suggestions for the improvement of reliability of transmission line, this method gived a fixed set of analytical steps, applicable to the random variable for calculating structural reliability index, arbitrary conditions the convergence speed and high precision.
2. Reliability Analysis of Transmission Lines Under Ice-Wind Combination

In this paper, a single transmission tower was selected as the research object to model its reliability analysis under combination of ice and wind. The overall modeling flow chart was shown in figure 1. It mainly included the following parts: (1) Collected the statistical parameters of load and resistance in the design of transmission lines, and determined the probability distribution type of each parameter. The resistance includes force resistance of poles and towers' axes, stability resistance of poles and towers' axes under compression, resistance of insulator strings, resistance of metal tools and resistance of guide wires; (2) according to the distribution function, selected the calculation method of the reliability index, respectively calculate the tower structure, insulator, metal and guide wire four components of the reliability index; (3) applied the series structure system to simulate the failure path of the system events, the overall system reliability index calculation; (4) according to the calculation results of the reliability index, put forward the reliability improvement measures of each part.

\[ \frac{Z}{\beta} = \frac{\mu}{\sigma} \]

Figure 1. Flow chart for reliability analysis of transmission line under combination of ice and wind.

3. Calculation Methods for Component Reliability and Statistical Characteristics of Basic Variables

This chapter first introduced the calculation method of each component reliability index in transmission line tower structure system, and then gave the statistical characteristics of load and resistance, which were the basic variables that affect the reliability of transmission line components.

3.1. Calculation Method of Component Reliability

The check point method in the first-order second-moment method often used for reliability analysis of tower structures was used to calculate the reliability index of components. When the structural function \( Z \) of the research object obeyed normal distribution, the calculation formula of the reliability index of components was:

\[ \beta = \frac{\mu_z}{\sigma_z} \]
where, $\mu_Z$ is the average value of function $Z$ and $\delta Z$ was the standard deviation. On the contrary, if the structural function does not obey the normal distribution, it is necessary to convert its variables into random variables subject to the normal distribution through equivalent normalization.

After equivalent normalization, the reliable index can be expressed as:

$$\beta = g \left( x_1, x_2, \ldots, x_n \right) + \sum_{i=1}^{n} \left( \frac{\partial g}{\partial X_i} \right) \left( \mu_X - x_i \right) \left( \mu_X - x_i \right) \left( \frac{\partial g}{\partial X_i} \right) \left( \mu_X - x_i \right) \left( \frac{\partial g}{\partial X_i} \right) \sigma_i^{2^{1/2}}$$  \hfill (2)

where, sensitivity coefficient of function composed of random variables can be expressed as:

$$\alpha_X = - \left( \frac{\partial g}{\partial X_i} \right) \sigma_i \left( \frac{\sum_{i=1}^{n} \left( \frac{\partial g}{\partial X_i} \right) \sigma_i^{2^{1/2}}}{\sum_{i=1}^{n} \left( \frac{\partial g}{\partial X_i} \right) \sigma_i^{2^{1/2}}} \right)$$  \hfill (3)

Coordinate of check calculation point:

$$x^*_i = \mu_X + \alpha_X \sigma_i \beta \quad (i=1, 2, \ldots, n)$$  \hfill (4)

The mean value, standard deviation, reliability index and sensitivity coefficient of equivalent normal random variable were all functions of the value of checking points. The reliability index were to be calculated by equivalent iterative calculation method. If $\|x^{(1)} - x^{(0)}\| \leq \epsilon$, $\epsilon$ was the specified allowable error, it will be terminated.

3.2. Statistical Characteristics of Permanent Loads

In the analysis of structural reliability, normal distribution was often used to describe the probability distribution of random variables such as material properties and permanent loads. In the transmission line, the permanent load was mainly the deadweight of tower structure, insulator and guide wire, which was denoted by $G$. Introduce the coefficient of variation, $\delta = \sigma / \mu$ and referred to the existing statistical results, taking the ratio of the average weight to the standard value $G = 1.06k$, and the coefficient of variation $\delta = 0.07$.

3.3. Statistical Characteristics of Wind Loads

The current design specification and manual [9], in determining the basic wind speed, the meteorological stations should be in accordance with local 10 min interval average annual maximum wind speed of statistical samples, and USES the extremum I type distribution as a statistical model of probability distribution.

When the wind speed was 33 m/s (design base year), the probability distribution function of wind load was:

$$F_X(x) = \exp \left\{ - \exp \left[ - \alpha(x-u) \right] \right\}$$  \hfill (5)

In the type:

$$\alpha_t = \pi / \sqrt{\alpha_w} = 1.2826 / \sigma_{w_t}$$  \hfill (6)

$$u_t = \mu_{w_t} - 0.5772 / \alpha_t$$  \hfill (7)

In the type: $\mu_{w_t} = 1.007 W_e$, $\sigma_{w_t} = 0.193 W_e$, $W_e$ was the standard value of wind load specified in the code.

3.4. Statistical Characteristics of Icing Loads

Icing on transmission lines was widespread in China, and ice damage accidents have been occurred in transmission lines in many regions of China [10]. The formation of ice coating on the surface of transmission wires was mainly promoted by: lower temperature (-10-0 °C), higher air humidity
(relative humidity above 90%), and lower wind speed (generally 0-10 m/s) [11]. The ice loads were assumed to be the extremum I type distribution, and its annual maximum probability distribution function can be represented as:

\[ F_{\alpha}(x) = \exp\left\{-\exp[-\alpha_0 \{(x-u_0)\}]\right\} \]  

where, \(\alpha_0\) was the location parameter of the maximum weight distribution of icing. \(u_0\) --The relationship between them and the mean value and standard deviation of weight of icing cover was as follows:

\[ \mu_i = u_i + 0.5772/\alpha_0 \ldots \sigma_i = 1.2826/\alpha_0 \]  

4. Statistical Characteristics of Mechanics Resistance

In the analysis of structural reliability, the probability characteristics of random variables such as structural mechanics resistance were often described by lognormal distribution.

When random variables obeyed the lognormal, the probability distribution function was:

\[ F_{\alpha}(x) = \Phi\left(\ln \frac{x}{\mu_{\kappa}} / \sigma_{\kappa}\right) \]  

The statistical characteristics of load and resistance in transmission line design were shown in table 1.

| Table 1: Statistical Characteristics of Load and Resistance. |
|-------------------------------------------------------------|
| Load | k(Mean Value / Standard Value) | \(\delta\) | Probability Distribution |
|-------|-------------------------------|--------|------------------------|
| Load Permanent | Tower bar | 1.060 | 0.070 | Gauss |
| Load | Icing Insulator | 1.100 | 0.090 |
| Load | Icing 30m/s wind | 1.007 | 0.193 | Extremum I Type |
| Load | Icing 10m/s wind | 1.076 | 0.179 |
| Load | Icing Axial force on member | 1.134 | 0.117 |
| Load | Icing Members stabilized by axial compression | 1.185 | 0.150 |
| Load | Icing Insulator String | 1.209, 1.181, 1.162 | 0.009, 0.06, 0.06 |
| Load | Fitting | 1.394 | 0.166 |
| Load | C&GW | 1.081 | 0.093 |

**a** Ratio of mean value to \(w_i\).

**b** The ratio of the mean value to 0.00918 \(w_i\).

**c** The number of insulators in each string is 10, 15, and 20 respectively.

5. The Calculation Method of System Reliability Index

5.1. Tower Structure Subsystem

Transmission line towers were composed of multiple pole members. Under the joint action of pole member gravity, insulator gravity, guide wire gravity, wind load and icing load, tower forces are balanced to form a statically indeterminate structure. However, if one of the rods failed, the stress of the entire tower were to be distributed again. If multiple towers failed and these towers formed a failure path, the failure of the entire tower system were caused. As there may be multiple failure paths
leading to the failure of one tower system, and these failure paths were or logic for the failure of the whole tower system, it was necessary to calculate the reliability of the tower system under multiple failure paths by using the method of series structure system.

Suppose that the series system has \( n \) function function, and the function of the \( i \) link is:

\[
Z_i = R_i - S_{i\Delta} - S_i - S_{wi}.
\]

(11)

In the type, \( R_i, S_{i\Delta}, S_i \), and \( S_{wi} \) — The resistance of the first member, the axial force generated by the dead weight of the member, the axial force generated by the icing load, and the axial force generated by the wind load. Normalize the equivalent of random variables and carry out iterative calculation to obtain the reliability index \( \beta_i \) and sensitivity coefficient of the first link \( \alpha_{R_i}, \alpha_{S_{i\Delta}}, \alpha_{S_i}, \) and \( \alpha_{S_{wi}} \) were expressed as:

\[
\beta_i = \mu_{R_i} - \mu_{S_{i\Delta}} - \mu_{S_i} - \mu_{S_{wi}}/\sqrt{\sigma_{R_i}^2 + \sigma_{S_{i\Delta}}^2 + \sigma_{S_i}^2 + \sigma_{S_{wi}}^2}.
\]

(12)

\[
\alpha_{R_i} = -\sigma_{R_i}/\left((\sigma_{R_i}^2 + \sigma_{S_{i\Delta}}^2 + \sigma_{S_i}^2 + \sigma_{S_{wi}}^2)^{1/2}\right).
\]

(13)

\[
\alpha_{S_{i\Delta}} = \sigma_{S_{i\Delta}}/\left((\sigma_{R_i}^2 + \sigma_{S_{i\Delta}}^2 + \sigma_{S_i}^2 + \sigma_{S_{wi}}^2)^{1/2}\right).
\]

(14)

\[
\alpha_S = \sigma_S/\left((\sigma_{R_i}^2 + \sigma_{S_{i\Delta}}^2 + \sigma_{S_i}^2 + \sigma_{S_{wi}}^2)^{1/2}\right).
\]

(15)

\[
\alpha_{S_{wi}} = \sigma_{S_{wi}}/\left((\sigma_{R_i}^2 + \sigma_{S_{i\Delta}}^2 + \sigma_{S_i}^2 + \sigma_{S_{wi}}^2)^{1/2}\right).
\]

(16)

The correlation coefficient between the I member and the j member can be calculated as follows:

\[
\rho_{ij} = \alpha_{R_i} \alpha_{R_j} + \rho_{S_{i\Delta}S_{j\Delta}} \sigma_{R_i}^2 + \alpha_{S_i} \alpha_{S_j} + \alpha_{S_{wi}} \alpha_{S_{wj}}.
\]

(17)

In the type, \( \rho_{S_{i\Delta}S_{j\Delta}} \) — The correlation coefficient between the axial forces generated by the dead weight on the member was related to the positions of the two members, taking 0.5.

The calculation of system reliability was a high-dimensional integral problem. In practice, simplified approximate calculation method was generally adopted:

\[
p_{fs} = 1 - \int_{-\infty}^{+\infty} \prod_{i=1}^{n} \Phi(\sqrt{\beta} + \beta_i)/\sqrt{2\pi} \phi(\beta) \Phi(\beta) dy
\]

(18)

Among them:

\[
\sigma = \sqrt{\frac{1}{n(n-1)} \sum \rho_i}
\]

(19)

where, \( \Phi(\cdot) \) was the probability distribution function of random variables subject to standard normal distribution, and \( \phi(\cdot) \) was its probability density function.

The equivalent reliability index was:

\[
\beta_{fs} = -\Phi^{-1}(p_{fs})
\]

(20)

where, \( \Phi^{-1}(\cdot) \) was the inverse function of the probability distribution function, and the variable was the standard normal random variable.

5.2. Insulator Subsystem

The failure of insulators on a transmission tower was constructed into a series system. The calculation method of system reliability was the same as that of tower structure system. V' insulator was selected...
as the research object. When dead weight, icing and wind load act together, its stress state was shown in figure 2.

**Figure 2.** Force analysis diagram of V-shaped insulator string under wind load and icing load.

The function of the v-insulator was expressed as follows:

$$Z = R - \left(\sin \left(\phi + \alpha \right)/\sin 2\alpha\right)P$$

(21)

Among them:

$$P = \left(\frac{P_1^2 + (W_1 + W_2)^2}{2}\right)^{1/2}, \quad \phi = \tan^{-1}\left(\frac{P_0}{(W_1 + W_2)}\right)$$

(22)

In the type,

- $P$ —— The composite load under the maximum wind load of the wire;
- $P_0$ —— The maximum wind load of the wire, $P_0 = P_{h L}$;
- $w$ —— Dead load of wire, $W_1 = L_1 W_1$;
- $\phi$ —— Ice load;
- $P_1$ —— Composite load on insulator string 2;
- $L_1, L_2$ —— Horizontal and vertical spacing of wires;
- $W_1, W_2$ —— Dead load of unit length wire and maximum wind load of wire;
- $\phi$ —— Maximum wind deflection of the wire;
- $\alpha$ —— The half of the Angle of a v-insulator string.

The system reliability index and sensitivity coefficient of variable of v-insulator subsystem were calculated by using the method in section 3.1 of this paper.

5.3. Hardware Subsystem and Lead Wire Subsystem

The function of the hardware was:

$$Z = R - \left[\left(\frac{L_1 W_1}{W_2}\right)^2 + \left(L_1 W_2\right)^2\right]^{1/2}$$

(23)

where, $R$ was the resistance of suspension clip (random variable); $W_1$ — wind load (random variable) when the wire is icing; $W_2$ — vertical load (random variable) when the wire was icing.

The function of the Conductor and Ground wire were:
\[ Z = R - T_0 - \sum T_i \]  

(24)

where, \( R \) -- resistance of the conductor (random variable); \( T_0 \) -- tension (random variable) generated by permanent load on the guide wire; \( T_i \) -- the \( i \) tension generated by the first variable load on the conductor (random variable).

The system reliability index and sensitivity coefficient of variables of the hardware subsystem and the lead wire subsystem were calculated by the method in section 3.1 of this paper.

6. Calculation of Examples and Analysis of Lifting Measures

6.1. An example is Given to Calculate

In this paper, the 220 kV voltage grade steel pipe column SGZK4-48 straight line tower and SGJ-42 tensile tower were taken as research objects, and the parameters were shown in table 2. The reliability index of each element of the two tower types under the condition of basic wind speed of 33 m/s and ice cover thickness of 10 mm were calculated.

| Tower Type | Insulator Type | Conductor Type | The tension load of conductors under different conditions | \( T_{\text{max}} \) (kN) | \( T_{\text{broken}} \) (%) | \( T_{\text{imbalance}} \) (%) |
|------------|----------------|----------------|----------------------------------------------------------|--------------------------|---------------------------|---------------------------|
| SGZK4-48   | V Type         | LGJ-400/35     |                                                          | 19.697                   | 25                        | 10                        |
| SGJ-42     |                | LGJ-630/45     |                                                          | 19.74                    | 70                        | 30                        |

According to the method in chapter 3 of this paper, the component reliability index and sensitivity coefficient of each variable of tower structure, insulator, metal implement and guide wire under ice-wind combination were calculated as shown in tables 3-6 respectively. According to the method in chapter 4 of this paper, the system reliability index and sensitivity coefficient of equivalent function of the four subsystems were calculated as shown in table 7.

Table 3. Component Reliability Indicators and Sensitivity Coefficients of Variables for Tower Structures.

| Tower Type | No. | \( \beta_{\text{tower}} \) | \( \alpha_G' \) | \( \alpha_W' \) | \( \alpha_G'' \) | \( \alpha_W'' \) | \( \alpha_I'' \) |
|------------|-----|--------------------------|----------------|----------------|----------------|----------------|----------------|
| SGZK4-48   | 1   | 8.269428                 | 0.002835       | 0.008911       | 0.811271       | 0.584596       |
|            | 2   | 8.613787                 | 0.003052       | 0.008254       | 0.807118       | 0.590324       |
| SGJ-42     | 1   | 5.442251                 | 0.001223       | 0.00441        | 0.848708       | 0.528843       |
|            | 2   | 5.689462                 | 0.001311       | 0.004097       | 0.846802       | 0.531891       |

Table 4. Component Reliability Indicators of Insulators and Sensitivity Coefficients of Variables.

| Tower Type | Conductor & GW | \( \beta_{\text{insulator}} \) | \( \alpha_G' \) | \( \alpha_G'' \) | \( \alpha_W' \) | \( \alpha_W'' \) | \( \alpha_I'' \) |
|------------|----------------|--------------------------|----------------|----------------|----------------|----------------|----------------|
| SGZK4-48   | GW             | 14.840                   | -0.563         | 0.023          | 0.008          | 0.826          |
|            | Conductor      | 7.828                    | -0.438         | 0.042          | 0.008          | 0.898          |
| SGJ-42     | GW             | 16.653                   | -0.615         | 0.022          | 0.763          | 0.199          |
|            | Conductor      | 10.632                   | -0.552         | 0.066          | 0.827          | 0.086          |
Table 5. Component Reliability Indicators and Sensitivity Coefficients of Variables for Metal Fittings.

| Tower Type | Component & GW | $\beta_{Metal~Fittings}$ | $\alpha_R$ | $\alpha_G$ | $\alpha_W$ | $\alpha_I$ |
|------------|----------------|--------------------------|-----------|-----------|-----------|-----------|
| SGZK4-48   | GW             | 13.549                   | -0.60703  | 0.001     | 0.795     | 0.004     |
|            | Conductor     | 9.014                    | -0.5307   | 0.008     | 0.847     | 0.008     |
| SGJ-42     | GW             | 14.286                   | -0.62526  | 0.023     | 0.000     | 0.780     |
|            | GW             | 7.943                    | -0.51738  | 0.041     | 0.000     | 0.855     |

Table 6. Component Reliability Indicators and Sensitivity Coefficients of Variables for Grounding Wires.

| Tower Type | Component & C&GW | $\beta_{Ground~Wires}$ | $\alpha_R$ | $\alpha_G$ | $\alpha_W$ | $\alpha_I$ |
|------------|-----------------|-------------------------|-----------|-----------|-----------|-----------|
| SGZK4-48   | GW              | 7.211                   | -0.301    | 0.048     | 0.030     | 0.952     |
|            | Conductor       | 12.374                  | -0.420    | 0.075     | 0.031     | 0.904     |
| SGJ-42     | GW              | 9.452                   | -0.3458   | 0.047     | 0.028     | 0.937     |
|            | Conductor       | 13.095                  | -0.448    | 0.096     | 0.036     | 0.888     |

Table 7. System reliability indices and sensitivity coefficients of equivalent function for each subsystem of transmission line tower-line structure.

| Tower Type | Components | $\beta$ | $\alpha_R$ | $\alpha_G$ | $\alpha_W$ | $\alpha_I$ |
|------------|------------|--------|-----------|-----------|-----------|-----------|
| SGZK4-48   | Tower      | 7.9726 | 0.403     | 0.375     | 0.045     | 0.625     |
|            | Insulator  | 7.576  | -0.539    | 0.052     | 0.017     | 0.838     |
|            | Fittings   | 8.874  | -0.550    | 0.007     | 0.834     | 0.007     |
|            | C&GW       | 6.964  | -0.391    | 0.068     | 0.030     | 0.916     |
|            | Tower      | 5.3400 | 0.535     | 0.246     | 0.046     | 0.613     |
| SGJ-42     | Insulator  | 10.436 | -0.568    | 0.055     | 0.811     | 0.115     |
|            | Fittings   | 7.674  | -0.607    | 0.052     | 0.001     | 0.790     |
|            | C&GW       | 9.314  | -0.422    | 0.083     | 0.032     | 0.901     |

6.2. Analysis of Wind and Ice Resistance Lifting Measures

GB 50068-2001 [7] stipulates that the target reliability index of brittle failure of structural components is 4.2 and that of ductile failure is 3.2. Starting from the weak components with low component reliability index in Table 3, these components were strengthened appropriately to improve the component reliability that can easily evolve into failure points. By Tables 4 and 5 shown that straight line tower insulator of the wire and the wire tension tower of hardware component reliability was relatively low, in the disaster prevention for this two parts corresponding to strengthen, as in "V" by adding child spacing on insulator string rod decrease offset under wind load, to alleviate the imbalance between the insulator string stress, the hardware with large mechanical strength, etc. In addition, among the reliability index of the tower-conductor and GW system, the GW system was on the low side in a straight line tower, which shown that under the combination of ice wind, conductor and ground wire break line drop probability was bigger, from Table 6 can be seen, lowest component reliability index was ground wires, therefore, it was necessary to take corresponding measures the transmission line ground wire in the area of ice disaster and wind disaster occurred frequently, especially line tower, reasonable reduce the span transmission lines, wind and ice disaster environment more reasonable to increase the number of transmission tower, wire tension, to reduce the transmission line can effectively reduce the harm caused by the line galloping. It indicated from Table 7 that, under rated icing load and rated wind load, the system reliability index of each subsystem of transmission
line tower line structure was greater than the target reliability index specified in the specification, among which, the system reliability index of tension tower structure was lower than that of suspension tower under the same environment. Therefore, under the combination of ice and wind load, it was necessary to strengthen the allocation of disaster prevention measures.

7. Conclusion
In this paper, through modeling the reliability analysis method of transmission line tower structure system under the combination of ice and wind loads, the system reliability analysis and calculation are carried out by using steel pipe pole suspension tower SGZK4-48 and tension tower SGJ-42 as examples respectively, and the following conclusions are mainly obtained:

(1) The system reliability index of tensile tower was lower than that of suspension tower, and the component reliability of tensile tower was generally lower under the combination of icing load and wind load.

(2) The system reliability index of the conductor and ground wire subsystems are low, and the element reliability index of the ground line is the lowest in the tower-line system of the suspension tower.

(3) The reliability of insulators and fittings of wires in suspension tower is relatively low.

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Reference
[1] LU Jia-zheng ZENG Min, TIAN Ling, et al. Microtopography based icing grades judging method for transmission lines [J]. Journal of Electric Power Science and Technology, 2013, 28(4): 24-30
[2] JIANG Xingliang, ZHANG Zhijin, HU Qin, et al., Thinkings on the Restrike of Ice and Snow Disaster to the Power Grid [J]. High Voltage Engineering, 2018, 44(02):463-469
[3] Zhang Haijie, Analysis of galloping of transmission lines and preventive measures [J]. Electronic Test, 2018(20):100-101
[4] YANG Jingbo, LI Zheng. YANG Fengli et al. Analysis of the Features of Covered Ice and Collapsed Tower of Transmission Line Snow and Ice Attacked in 2008 [J]. Advances of Power System & AMP; Hydroelectric Engineering, 2008, 24(4):4-8
[5] Li jiancao. Study on structural reliability of self-supporting tower in transmission line [D]. Harbin: Harbin engineering university, 2009
[6] Gu Yu. Structural design and reliability analysis of 220kV transmission tower [D]. Dalian university of technology, 2014
[7] GB 50068-2001 Unified Standard for Reliability Design of Building Structures [S]. Beijing: China Construction Industry Press, 2001
[8] ISO 2394:1998 General Principle on Reliability for Structures [S]. International Organization for Standardization, Printed in Switzerland, 1998
[9] GB 50545-2010 code for design of 110 kV-750 kV overhead transmission lines [S]. Beijing: China planning press, 2010
[10] Jiang xingliang, Yi Hui. Icing and protection of transmission lines [M]. Beijing: China electric power press, 2002
[11] Liu heyun. Theory and application of icing prevention for overhead wires [M], Beijing, China railway publishing house, 2001