Buckling Analysis of Transmission Tower Considering Ice Load

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Abstract. Transmission lines are important lifeline projects. The stable operation of transmission lines is closely related to economic and social security and stability. Ice storm seriously affects the safety of transmission lines. The simulation analysis of ice damage of transmission tower structure has important theoretical significance and engineering value. In this paper, the finite element software ANSYS is used to analyze the buckling of the self-supporting tower based on eigenvalue buckling analysis and nonlinear buckling analysis. The effects of vertical span, uniform ice coating, uneven ice coating, and wind load were considered. The ice thickness of the tower buckling is reduced with the vertical span decreasing under uniform ice coating the transmission line. As the coefficient of unevenness increases, the thickness of the unstable ice coating of the tower drops sharply. The unstable wind speed decreases with the increase of ice thickness.

1. Introduction

Transmission lines are important lifeline projects. The stable operation of transmission lines is closely related to people's lives and economic security. In early 2005 and early 2008, China’s transmission lines were seriously damaged by the ice disaster [1]. Two typical collapse towers in China induced by the ice storm in 2008 are illustrated in figure 1.

From February 7 to 17, 2005, a rare rain and snow disaster in history raided Hunan province in China. There have been accidents such as electric power line ice flashing, tower collapsed and wire broken. 24 towers of three 500kV lines and 18 towers of six 220kV lines collapsed due to overwhelming. At the beginning of 2008, the southern part of China suffered severe freezing disasters affected by the cold and warm air. 678 towers of 500 kV AC/DC transmission lines collapsed and 119 lines stopped running. 1432 towers of 220 kV transmission lines collapsed and 343 lines stopped running [2-4]. The ice disaster caused a major loss to the national economy and people’s lives and property.

2. Buckling analysis

2.1. Eigenvalue buckling analysis

Eigenvalue buckling analysis, also known as linear buckling analysis, is used to analyze the buckling strength of an ideal structure. The advantage is that the critical load of the structure can be obtained without nonlinear analysis of the structure, and on this basis, it can provide a reference for nonlinear buckling analysis. The disadvantage is that the initial defects and geometric nonlinear deformation characteristics of the truss structure are not considered in the analysis process, and the calculation results are generally conservative [5].
In the stable equilibrium state, considering the influence of axial force or medium internal force on the bending deformation [6-8], the equilibrium equation of the structure is obtained according to the principle of resident potential energy, as shown in equation 1.

$$([K_e] + [K_o])\{U\} = \{P\}$$  \hspace{1cm} (1)

where $[K_e]$ is the stiffness matrix of the structure, $[K_o]$ is the geometric stiffness matrix of the structure, $\{U\}$ is the node displacement vector, and $\{P\}$ is the node load vector. Equation 1 is also the equilibrium equation for geometric nonlinear analysis.

In order to obtain the indifferent equilibrium state [6-8], the second variation of the potential energy of the system should be zero, that is,

$$([K_e] + [K_o])\delta\{U\} = 0$$  \hspace{1cm} (2)

The eigenvalue equation can be obtained [6-8], as shown in Equation 3.

$$([K_e] + \lambda_i[K_o])\{\varphi_i\} = 0$$  \hspace{1cm} (3)

where $\lambda_i$ is the i-th eigenvalue, $\{\varphi_i\}$ is the eigenvector corresponding to $\lambda_i$, i.e., the buckling mode.

2.2. Nonlinear Buckling Analysis
The nonlinear buckling analysis of the tower structure can be carried out based on the results of eigenvalue buckling analysis as its initial defects. In this paper, the non-linear equilibrium path is tracked by the equal arc method. In the iterative process of nonlinear buckling analysis, the load convergence criterion shown in equation 4 was chosen as the criterion for convergence [9, 10].

$$\sqrt{\{g\}^T\{g\}} \leq \beta\sqrt{\{q\}^T\{q\}}$$  \hspace{1cm} (4)

where $g$ is the imbalance node force vector, $q$ is the reference load vector, and $\beta$ is the parameter, which is $10^{-5}$.

3. Finite element model
The finite element model of the tower line system is mainly composed of three parts: power transmission lines (wires, ground lines), insulators and transmission towers. In this paper, the 5A-ZBC2 tower is used to build the finite element model of transmission tower line system. The geometric dimensions are shown in figure 2. The transmission line system in this study includes 3 towers, 2 ground wires and 3 groups of conductors, as shown in figure 3.

The structure of the transmission tower has strong geometric nonlinearity. The BEAM188 space beam element is used to simulate the poles of the transmission tower. The element is the characteristics of stress stiffening and large deformation. LINK 10 is used to simulate the transmission line. LINK10 is a 3D rod element which can only withstand axial tension or pressure. It can be used to simulate cables or gaps. The insulator is simulated by LINK8 element, which has the characteristics of plasticity, expansion, stress stiffening and large deformation.
4. Ice load and wind load of transmission line

4.1. Ice load of tower and insulator
The ice load (N/m²) per unit surface area of the tower members and insulators is

\[ q_i = 0.6b\alphai\gamma \]  

(5)

where \( b \) is the basic ice thickness determined by engineering experience (mm), \( \alpha_i \) is the height increment coefficient of the ice coating thickness, and \( \gamma \) is the ice bulk density which is 9kN/m³ [11].

4.2. Ice load of wire
Due to the action of the wind, the shape of the ice coating the wire is very irregular. It can be simplified to a circular shape when the ice load is calculated. The ice load (N/m) of the wire and ground wire is

\[ q_l = \pi b\alpha_i\alpha_z(d + b\alpha_i\alpha_z)\gamma \]  

(6)

where \( \alpha_i \) is the ice thickness correction factor related to the diameter of the guide (ground) line, \( d \) is the diameter of the wire or ground line (m) [11].

4.3. Wind load of transmission tower
The standard wind load value of the tower \( W_T \) (N) is as follows:

\[ W_T = W_0 \cdot \mu_z \cdot \mu_s \cdot \beta_z \cdot A_z \]  

(7)

where \( W_0 \) is the standard value of basic wind pressure (N/m²), \( \mu_z \) is the height transformation coefficient of wind pressure, \( \mu_s \) is the shape coefficient, \( \beta_z \) is the wind load adjustment coefficient of tower, and \( A_z \) is the calculation value of withstand wind pressure area (m²) [11].

4.4. Wind load of insulator
The standard wind load value of insulator string \( W_I \) (N) is determined by the following formula:

\[ W_I = W_0 \cdot \mu_z \cdot A_I \]  

(8)

where \( A_I \) is the calculation value of insulator withstand wind pressure area (m²) [11].

4.5. Wind load of wire and ground line
The standard wind load value of wire and ground line \( W_L \) (N) is determined by the following formula:

\[ W_L = \alpha \cdot W_0 \cdot \mu_z \cdot \mu_w \cdot \beta_z \cdot d \cdot L_p \cdot \sin^2 \theta \]  

(9)
where $\alpha$ is wind pressure unevenness coefficient, $\beta_c$ is wind load adjustment factor of 500kV line, $\mu_{wc}$ is shape coefficient of wire and ground line, $d$ is the outer diameter of the wire or the calculated outer diameter of the wire(m), $L_p$ is the horizontal span of transmission lines(m), and $\theta$ is the angle between the wind direction and the wire [11].

5. Analysis results

5.1. Buckling Analysis of Tower Under Uniform Ice Coating

The buckling mode of the tower under uniform ice coating on the transmission line is shown in figure 4. The relationship between the ice thickness of the tower buckling and the vertical span is shown in figure 5. The ice thickness of the tower buckling is reduced with the vertical span decreasing under uniform ice coating the transmission line.

![Figure 4. The buckling mode of tower under uniform ice coating.](image)

![Figure 5. The relationship between the ice thickness of the tower buckling and the vertical span.](image)

5.2. Buckling analysis of tower under uneven ice coating

In order to consider the influence of uneven ice coating on the stability of the tower in the same span, the unevenness coefficient $\rho$ is used to indicate the uneven ice coating degree of the tower

$$\rho = \frac{\Delta l}{\sqrt{(L_c)^2-(\Delta l)^2}}$$

(10)

where $\Delta l$ is the horizontal offset along the line of suspension point of the wire on the suspended insulator string (m), and $L_c$ is the length of suspension insulator string (m).

![Figure 6. The buckling mode of the tower under different unevenness coefficients.](image)

Figure 6 shows the buckling mode of the tower under different unevenness coefficients. As the unevenness coefficient increases, the area of the buckling failure of the tower is expanding. The damage zone extends from one rod to multiple rods. The relationship between the ice thickness and
unevenness coefficient is illustrated in figure 7. The unbalanced tension increases with the unevenness coefficient increases. So the thickness of the unstable ice coating of the tower drops sharply with the coefficient of unevenness increasing.

5.3. Buckling analysis of tower considering wind load
Wind load is also one of the causes of the collapse of the tower. The relationship between the ice thickness and unstable wind speed is illustrated in figure 8. The unstable wind speed decreases with the increase of ice thickness. When the ice thickness and wind speed of the transmission line exceed the curve of figure 8, the tower will be in danger of collapse.

![Figure 7. The relationship between the ice thickness and unevenness coefficient.](image1)

![Figure 8. The relationship between the ice thickness and unstable wind speed.](image2)

6. Conclusions
The finite element simulation of the transmission tower buckling under ice coating is carried out in this paper. The results show that the ice thickness of the tower buckling is significantly reduced with the increase of uneven ice coating level, and the instability damage area is significantly expanded. As the wind speed increases, the ice thickness of the tower bulking decreases significantly.

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