Characteristic Analysis and Prevention of Ice Galloping of Transmission Lines Based on Finite Element Method

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Abstract. Ice galloping is one of the disasters that have the greatest impact on the safe operation of transmission lines in winter. This article analyze the characteristics and prevention method of ice galloping of electric grid transmission lines based on finite element method. The amplitude and time response of transmission line during ice galloping can be obtained. A new type of efficient anti-galloping interface spacer is proposed, which can reduce the galloping amplitude. The effectiveness of the proposed method and model is verified by application examples.

Keywords: Ice galloping; Electric grid transmission lines; Finite element method; Prevention method.

1. Introduction
In winter, icing is the biggest harm to the safe operation of electric grid. The main threats to transmission lines caused by icing are: line or tower breaking under heavy ice, light ice galloping, ice-shedding jumping and ice melting flashover[1-3].

The ice galloping is likely to cause large amplitude vibration of the transmission line, which leads to the decrease of air gap between phases and thus the inter phase discharge[4-7]. Moreover, ice galloping can cause damage to insulator, hardware and tower.

Many factors lie in the determination of ice galloping amplitude, including ice shape and thickness, wind speed and direction, fault span, elastic modulus of transmission line, etc.[8-11]

In order to ensure the safe operation of electric grid in winter, it is very important to study the characteristics of ice galloping of transmission lines.

2. Basic Assumptions of Finite Element Method

2.1. Structure of Finite Element Method
The schematic diagram of single span transmission line is shown in Figure 1, in which the transmission line hang freely on the insulators fixed on towers.

![Figure 1. Schematic diagram of single span transmission line.](image-url)
In the finite element method shown by Figure 2, the transmission line is divided into several nodes connected by straight rods.

![Figure 2. Schematic diagram of finite element method.](image)

2.2. Mass of Nodes and Rods
The mass of the transmission line is concentrated on the nodes, while the mass of the straight rods are 0. The mass of each node is equal to half of the sum of the straight rods’ mass on both sides of the node.

2.3. Elasticity and Rigidity of Rods
The straight rods are ideal flexible and can neither bear bending moment nor bear compression. The tensile action of the straight rods accord with Hooke's law.

3. Dynamic Calculation

3.1. Kinetic Equation
The kinetic equation are as follows, where \(m_i\) denotes mass of node \(i\), \((x, y, z)\) denote location of node \(i\), \(\zeta\) denotes damping coefficient, and \((F_{ix}, F_{iy}, F_{iz})\) denote force of node \(i\).

\[
\begin{align*}
    m_i \ddot{x}_i + \zeta \dot{x}_i &= F_{ix} \\
    m_i \ddot{y}_i + \zeta \dot{y}_i &= F_{iy} \\
    m_i \ddot{z}_i + \zeta \dot{z}_i &= F_{iz}
\end{align*}
\]

(1)

3.2. Solution Method of Difference Equation
The central difference algorithm is used to solve the velocity and acceleration.

\[
\begin{align*}
    \dot{x}_i &= \frac{x_i(t + \Delta t) - x_i(t - \Delta t)}{2\Delta t} \\
    \dot{y}_i &= \frac{y_i(t + \Delta t) + x_i(t - \Delta t) - 2x_i(t)}{\Delta t^2}
\end{align*}
\]

(2)

According to the dynamic equation and the difference equation, the iterative equation can be obtained.

\[
\begin{align*}
    x_i(t + \Delta t) &= \frac{F_{ix} + \frac{2m_i}{\Delta t^2} x_i(t) - \left(\frac{m_i}{\Delta t^2} - \frac{c}{2\Delta t}\right)x_i(t - \Delta t)}{\frac{m_i}{\Delta t^2} + \frac{\zeta}{2\Delta t}} \\
    y_i(t + \Delta t) &= \frac{F_{iy} + \frac{2m_i}{\Delta t^2} y_i(t) - \left(\frac{m_i}{\Delta t^2} - \frac{c}{2\Delta t}\right)y_i(t - \Delta t)}{\frac{m_i}{\Delta t^2} + \frac{\zeta}{2\Delta t}} \\
    z_i(t + \Delta t) &= \frac{F_{iz} + \frac{2m_i}{\Delta t^2} z_i(t) - \left(\frac{m_i}{\Delta t^2} - \frac{c}{2\Delta t}\right)z_i(t - \Delta t)}{\frac{m_i}{\Delta t^2} + \frac{\zeta}{2\Delta t}}
\end{align*}
\]

(3)
4. Initial Shape Analysis

4.1. Catenary Equation

Figure 3. Schematic diagram of catenary equation.

The solution of catenary equation is as follows.

\[
\begin{align*}
\frac{F_2}{T_0} &= y' \\
\frac{F_1}{T_0} &= (y + dy)' \\
F_1 &= F_2 + qg \sqrt{(dx)^2 + (dy)^2} \\
y &= \frac{T_0}{qg} \cosh \left[ \frac{qg}{T_0} (x + C_1) \right] + C_2
\end{align*}
\]

4.2. Initial Form Finding

The initial form finding step is used to determine the original shape of icing transmission lines when there is no wind. According to the catenary equation, initial form finding equations are as follows.

\[
\begin{align*}
x_i &= \frac{iL}{N} \\
T_i &= T_0 \cosh \left( \frac{qg(x_i + C_1)}{T_0} \right) \\
I_{oi} &= \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \\
k_i &= \frac{EA}{l_{oi}}
\end{align*}
\]

5. Aerodynamic Parameters

Due to the irregular shape of transmission line icing, the lifting force, resistance force and torsion force will be generated when the wind blows over the iced line.
In order to calculate aerodynamic parameters ($C_D$, $C_L$, $C_M$), the hydrodynamics simulation is carried out in ANSYS™. For example, considering wind speed of 12m/s, line diameter of 26mm, and ice thickness of 12mm, the simulation results under different attack angle are as follows. Velocity field and pressure field under attack angle of 0°, 30°, and 60° is shown in Figure 5, Figure 6 and Figure 7 respectively. Figure 8 shows the diagram of aerodynamic of parameters.

$$F_D = 0.5 \rho v^2 DC_D$$  \(10\)

$$F_L = 0.5 \rho v^2 DC_L$$  \(11\)

$$M = 0.5 \rho v^2 D^2 C_M$$  \(12\)

In order to calculate aerodynamic parameters ($C_D$, $C_L$, $C_M$), the hydrodynamics simulation is carried out in ANSYS™. For example, considering wind speed of 12m/s, line diameter of 26mm, and ice thickness of 12mm, the simulation results under different attack angle are as follows. Velocity field and pressure field under attack angle of 0°, 30°, and 60° is shown in Figure 5, Figure 6 and Figure 7 respectively. Figure 8 shows the diagram of aerodynamic of parameters.

$$C_D = 2.36 + 0.012 \cos \alpha - 1.05 \cos 2\alpha$$  \(13\)

$$C_L = -0.37 \sin \alpha + 0.88 \sin 2\alpha + 0.55 \sin 3\alpha + 0.039 \sin 4\alpha$$  \(14\)

$$C_M = -0.81 \sin \alpha - 0.78 \sin 2\alpha - 0.042 \sin 3\alpha - 0.15 \sin 4\alpha$$  \(15\)

6. Case study
In January 2019, one transmission line of Hunan province electric grid, Luxian line, tripped due to ice galloping. The detailed parameters of the fault line are as follows.
Figure 9. Diagram of numerical case.

Table 1. Detailed parameters of the fault line.

| Parameter type       | Value       |
|----------------------|-------------|
| Fault span           | 629 (m)     |
| Previous span        | 523 (m)     |
| Next span            | 347 (m)     |
| Height difference    | 30 (m)      |
| Elastic modulus      | 65000 (N/mm²) |
| Cross section area   | 425.24 (mm²) |
| Linear density       | 1349 (kg/km) |
| External diameter    | 26.82 (mm)  |
| Icing thickness      | 12 (mm)     |
| Ice density          | 0.676 (g/mm³) |
| Wind speed           | 12m/s       |

Computing software and platform:
1) CPU: Intel Xeon E5-2630 v2 @ 2.60GHz
2) CPU cores: 6
3) Software: Fortran f90

Calculation time of 1 million iterations: 33s.

According to the simulation results, the amplitude and time response of the transmission lines are as follows. In Figure 10, the amplitude of upper and lower transmission lines from t=0s to t=10s is simulated. It can be seen from the figure that when the traditional interphase spacer is used, the amplitude of line galloping is large.

Figure 10. Amplitude and time response of transmission lines.

Traditional interphase spacer is connected with a hinge in the middle. In order to reduce the galloping amplitude, a new type of efficient anti-galloping interface spacer is proposed, where the hinge is replaced by a buffer device with damping pads.
Figure 11. Traditional interphase spacer (left) and efficient anti-galloping interface spacer (right).

As shown in Figure 12, when using the new type of efficient anti-galloping interface spacer, the amplitude of galloping is reduced by 63.9%, compared to Figure 10 with traditional interphase spacer. The mechanical energy is reduced by 50.1% as shown in Figure 13, while axial force is reduced by 68.5% as shown in Figure 14.

Figure 12. Amplitude and time response of transmission lines by efficient anti-galopping interface spacer.

Figure 13. Mechanical Energy of each node in transmission line.

Figure 14. Time response of pacer force during ice galloping.

7. Conclusion
This article analyzes the characteristic of ice galloping of transmission lines based on finite element method. Firstly, the structure of finite element method is built. Secondly, kinetic equation and difference equation method are used to calculate the dynamic response of transmission lines during ice galloping. Thirdly, initial shape analysis is used to determine the initial shape of transmission lines. Fourthly, the aerodynamic parameters under different attack angle are calculated via simulation. Fifthly, a new type of efficient anti-galloping interface spacer is proposed, which can reduce the galloping amplitude. Finally, the effectiveness of the proposed method and model is verified by application examples, using which the amplitude and time response of transmission line during ice galloping can be obtained.

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