Study on calculation model of wind deflection response of transmission line

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Abstract. The wind deflection angle is directly related to the electric gap and the construction cost of the transmission line, so the accuracy of the wind deflection calculation method and the reasonable value of the relevant parameters are very important for the safe operation and economic rationality of the transmission line. In this paper, based on the nonlinear transient analysis method, the characteristics of aerodynamic damping on the transient response of transmission line wind deflection are revealed. At the same time, according to the code of transmission line design in China, the static wind deflection calculation method is used to solve the static wind deflection angle of transmission line, and the dynamic and static calculation models of wind deflection angle are compared.

1. Introduction
Transmission tower is an important facility of power grid system. As the skeleton of supporting transmission line, transmission tower often suffers from failure or even collapse in extreme cases. The causes of transmission tower damage and tower collapse are different. The main influencing factors are the different load conditions and sizes, and the wind load often plays a controlling role in tower design.¹

The wind deflection angle is directly related to the electric gap and the construction cost of the transmission line, so the accuracy of the wind deflection calculation method and the reasonable value of the relevant parameters are very important for the safe operation and economic rationality of the transmission line. At present, only an empirical wind pressure nonuniformity coefficient is used in the design code of transmission line to consider the reduction of wind load caused by the spatial correlation of wind speed, and the static calculation of wind deflection is carried out by using the simple pendulum model. The accuracy of the results needs to be discussed. Because of not considering the effect of wind speed fluctuation and severe weather conditions such as thunderstorm, the calculated value of wind deflection is often not safe for design, which is one of the main reasons for frequent wind deflection accidents.²

The methods of calculating wind deflection are time domain method and frequency domain method. Although the time-domain method is slow in calculation and takes a lot of time to simulate the wind speed, it is based on the principle of numerical integration, which can better consider the impact of nonlinearity, which is very important for the transmission line system.³
Time domain method can also consider the spatial correlation of wind speed to better reflect the dynamic characteristics of wind deflection of transmission lines. Because the dynamic tension of the conductor needs to be analysed in the follow-up study, the time-domain method is used to calculate the dynamic response of wind deflection. 

2. Dynamic analysis of wind deflection response considering aerodynamic damping effect

According to the quasi steady assumption, the transient wind field based on the harmonic superposition method is transformed into the wind pressure time history, which is applied to each node of the transmission line model, and the dynamic response of the wind deflection of the conductor under the time-domain condition can be obtained through the nonlinear transient solution algorithm. In addition, when the transmission line vibrates in wind, the relative motion effect between the structure and the incoming flow will increase the damping of the power system, and the added damping is the aerodynamic damping attached to the structure, which has the characteristics of increasing with the increase of the average wind speed.

Transmission line has the characteristics of long span, small damping and large flexibility, which is a typical nonlinear structure sensitive to wind load. Therefore, whether the aerodynamic damping effect is taken into account when solving the wind deflection response of the conductor will have a significant impact on the wind deflection results.

Figure 1. Motion model of wire with multi degrees of freedom.

Figure 2. Calculation model of rigid straight bar method.

In order to explain the generation mechanism and action characteristics of aerodynamic damping of conductor in detail, the n-DOF multi span transmission line as shown in Figure 1 is introduced here. Under the action of wind load, the displacement vector $\mathbf{y}$ along the wind direction can be expressed as:

$$\mathbf{y} = [y_1, y_2, \ldots, y_n]^T$$

Where $y_i$ is the downwind displacement of point $i$, and the nonlinear motion equation of the corresponding transmission line can be written as follows:

$$M\ddot{\mathbf{y}} + C_{so} \dot{\mathbf{y}} + K_{r}(\mathbf{y})\mathbf{y} = \mathbf{F}$$

Here, $M$ and $C_{so}$ are the mass matrix and damping matrix of the conductor itself. $\ddot{\mathbf{y}}$ and $\dot{\mathbf{y}}$ are acceleration and velocity vectors of the system respectively. $K_{r}(\mathbf{y})$ is the tangent stiffness matrix considering the geometric nonlinear effect, which is related to the displacement state $\mathbf{y}$ of the structure:

$$K_{r}(\mathbf{y}) = K_L(K_N(K_{\sigma}(\mathbf{y}) + K_{\nu}(\mathbf{y})))$$

$K_L$, $K_N(\mathbf{y})$ and $K_{\sigma}(\mathbf{y})$ are linear stiffness matrix, nonlinear stiffness matrix and stress stiffness matrix respectively. $\mathbf{F}$ is the time history matrix of wind load acting on the transmission line structure. When the relative motion state of structure and incoming flow is not considered, $\mathbf{F}$ can be expressed as:

$$\mathbf{F} = \frac{1}{2} \rho C_{so}[A_1(\bar{U}_{c,1} + \bar{U}_1)^2, A_2(\bar{U}_{c,2} + \bar{U}_2)^2, \ldots, A_n(\bar{U}_{c,n} + \bar{U}_n)^2]^T$$

(4)
Where $\bar{U}_{i, z}$, $\bar{u}_i$ and $A_i$ are the average wind speed, fluctuating wind speed and effective windward area of point i respectively. $\rho$ and $C_D$ are the air density and the wire resistance coefficient, respectively.

It can be seen from equation (4) that the wind load acting on the conductor is only related to the wind speed and the aerodynamic parameters of the section without considering the aerodynamic damping. When considering the relative motion effect of conductor and incoming flow, the wind load $f$ at the right end of formula (4) is:

$$F = \frac{1}{2} \rho C_D [A_i (\bar{U}_{i, z} + \bar{u}_i - \bar{Y}_i)^2, A_i (\bar{U}_{i, z} + \bar{u}_i - \bar{Y}_i)^2, \ldots, A_i (\bar{U}_{i, n} + \bar{u}_n - \bar{Y}_n)^2]^T$$

(5)

Expand equation (5) to obtain the term related to the wire's own velocity $\dot{Y}_i$, which is aerodynamic damping. Substituting formula (5) into formula (2), we can get:

$$M \ddot{Y} + (C_{Str} + C_{aero}) \dot{Y} + K_f \dot{Y} = F_1 + F_2$$

(6)

Where $F_1$ and $F_2$ are respectively:

$$F_1 = \frac{1}{2} \rho C_D [A_i (\bar{U}_{i, z} + \bar{u}_i)^2, A_i (\bar{U}_{i, z} + \bar{u}_i)^2, \ldots, A_i (\bar{U}_{i, n} + \bar{u}_n)^2]^T$$

$$F_2 = \frac{1}{2} \rho C_D [A_i \dot{Y}_i^2, A_i \dot{Y}_i^2, \ldots, A_i \dot{Y}_n^2]^T$$

(7)

(8)

Because $F_2$ is the square term of traverse velocity, it is a small quantity and can be ignored. Therefore, the $C_{aero}$ on the left side of formula (6) is the aerodynamic damping matrix caused by the motion state of the conductor itself:

$$C_{aero} = \rho C_D \text{diag}[A_i (\bar{U}_{i, z} + \bar{u}_i), A_i (\bar{U}_{i, z} + \bar{u}_i), \ldots, A_i (\bar{U}_{i, n} + \bar{u}_n)]$$

(9)

It can be seen from the above formula that the aerodynamic damping is closely related to the wind speed around the transmission line. In addition, since the average wind speed $\bar{U}_{i, z}$ of each point on the transmission line is greater than the absolute value of fluctuating wind speed $\bar{u}_i$, the aerodynamic damping attached to the structure is always positive.

3. Dynamic calculation of wind deflection response

According to the quasi steady assumption, the wind speed time history based on the harmonic superposition method is transformed into the wind pressure time history.

$$F_y = \frac{1}{2} \rho DL_n C_D (U_z + \bar{u}_z)^2$$

(10)

Where $\rho$ is the air density, D is the equivalent windward diameter of the conductor, $L_n$ is the control length of the loading point, and $C_D$ is the resistance coefficient. $U_z$ and $\bar{u}_z$ are the average wind speed and fluctuating wind speed at z height respectively.

When the transmission line is subject to wind-induced vibration, the relative motion effect between the structure and the incoming current will produce aerodynamic damping. Because UHV transmission lines have the characteristics of long span, small damping and large flexibility, aerodynamic damping has a significant impact on the calculation of wind deflection response.

Considering the influence of aerodynamic damping and the relative velocity between the conductor and the incoming flow, the wind load acting on the structure surface is:

$$F_y = \frac{1}{2} \rho DL_n C_D (U_z + u_z - u_D)^2$$

(11)

Where $u_D$ is the velocity of the wire at the corresponding time.

After calculating the pressure time history, it is applied to each node of the transmission line model. In this paper, the nonlinear dynamic equation is solved by direct integration using the unconditionally stable Newmark method, and the displacement at the end of each time step is iterated by Newton Raphson method.
4. Static calculation of wind deflection response
For the calculation of line wind deflection, the rigid straight bar method is adopted in the current power industry standard in China. The rigid straight bar method is derived from static equilibrium. It regards the suspended insulator string as a rigid straight pole under the action of uniform load, concentrates the conductor mass and the wind load to the suspension point of the insulator string, and assumes that when the wind load reaches the static balance with the dead weight of the conductor and insulator string, the swing angle is the wind deflection angle.

As shown in Figure 2, the wind deflection angle of insulator string can be expressed as:

\[
\theta = \tan^{-1}\left(\frac{W_h + G_h / 2}{W_v + G_v / 2}\right)
\]

(12)

Where \( G_h \) and \( W_h \) are wind loads on insulator string and conductor respectively, and \( G_v \) and \( W_v \) are dead weight of insulator string and conductor respectively. It should be noted that the horizontal span of the tower where the insulator string is located should be used to calculate the wind load of the conductor. When determining the dead weight of the conductor, the vertical span shall be adopted, namely:

\[
W_h \approx p_h \left(\frac{l_1 + l_2}{2}\right) \quad W_v \approx p_v \left(\frac{l_1 + l_2}{2}\right) + T_0 \left(\frac{h_1 + h_2}{l_1 + l_2}\right)
\]

(13)

Where, \( p_h \) and \( p_v \) are the horizontal wind load and vertical load on the unit length of the conductor, \( l_1 \) and \( l_2 \) are the left and right span on both sides of the tower, and \( T_0 \) is the conductor tension. \( h_1 \) and \( h_2 \) are the height difference between the suspension points on both sides of the tower. When the suspension point of the tower is higher than the adjacent tower, its value is positive, otherwise its value is negative. For the horizontal wind load \( p_h \) on the unit length of conductor, the following formula shall be used for calculation according to the design code of transmission line:

\[
p_h = \alpha \omega_0 \mu_z \beta_c d \sin^2 \theta
\]

(14)

Where, \( \alpha \) is the wind pressure nonuniformity coefficient. \( \omega_0 \) is the basic wind pressure, which can be converted from the design reference wind speed. \( \mu_z \) is the wind pressure height variation coefficient, \( \beta_c \) is the shape coefficient, \( d \) is the wind load adjustment coefficient, \( \theta \) is the outer diameter of the conductor, and \( p_h \) is the angle between the wind direction and the line axis. The wind load on the insulator string is calculated by the following formula:

\[
G_h = \omega_0 \mu_z A_j
\]

(15)

Where \( A_j \) is the wind bearing area of insulator string.

5. Conclussion
When the wind deflection response of transmission lines is calculated based on the rigid straight bar method, the actual wind deflection angle of transmission lines will be underestimated, which is not safe for line design. Based on the finite element analysis method, this paper studies the wind-induced vibration response characteristics of the tower line coupling system, and derives the dynamic and static response calculation formulas of the wind deflection angle of the transmission line.

References
[1] Sun B.Q., Hou L., Meng X.B., et al. (2010) Analysis of wind - bias dynamic response of wire under different wind speeds. High voltage technology, 36: 2808-2813.
[2] Bian R., Xu X., Wang Y.F., Lou W.J. (2019) Simplified calculation method for dynamic wind-induced deflection of iced conductors and influencing factor analysis. Zhejiang Electric Power, 38: 35-41.
[3] Yang X., Pei H.K., Zhang Y.J. (2019) Design of wind load response on-line monitoring system based on ZigBee technology for electric transmission line. Modern Electronics
[4] Lou W.J., Bai H., Bian R., Zhang L.G. (2019) Value study on span reduction coefficient and non-uniformity coefficient of wind pressure of transmission lines. Zhejiang Electric Power, 38: 72-77.