Analysis on Mechanical Properties of Single Conductor Considering Flexural Stiffness under Wind Load

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Abstract. In order to study the effect of flexural stiffness on the mechanical properties of single conductor under wind load, a configuration function of the conductor considering stiffness is established in this paper. Based on the configuration function, the finite element model is established, and the effects of suspension point angle, span on the mechanical properties of down lead conductor under wind load are studied. The results show that, compared with the catenary model, the model in this paper is more consistent with the experimental fitting formula. The angle of the suspension point has obvious influence on the tension of down lead conductor. With the increase of the angle of the suspension point from 0° to 80°, the tension decreases by nearly one third. The bending moment is affected by the alignment, and the reverse sign appears with the increase of suspension point angle. When the redundancy rate is the same, the span increases from 2 m to 4 m, and the tension of the conductor decreases by 18%.

1. Introduction
The power system is the lifeblood of the national economy. With the development of society and economy, the degree of dependence on electricity in various fields is increasing. However, the increasing scale of power grid, the increasing capacity of power grid and the increasing geographical span increase the influence of severe meteorological conditions on the operation and inspection of power grid. Under the load of strong wind, wind-induced damage of down lead conductors and equipment connecting with the down lead conductors often occurs [1-4]. In order to analyze the mechanical characteristics of conductors, it is necessary to determine the shape of conductors first. For form-finding analysis study, Hong et al. simplified the conductor into a cable without bending stiffness and established the shape-finding function of the cable under gravity in 2001 [5]. And there have been many studies on the shape-finding of cable structure [6-8]. When considering the bending stiffness of conductors, Chen [9] et al. tested the bending stiffness of different types of single conductors through experiments, and proposed an effective simplified method of bending stiffness. Foti et al. improved the mechanical model considering the tension and bending stiffness of stranded conductors [10]. WAN Jian-cheng [11] conducted experimental research on the relation between sag and tension of single conductor and...
bundled conductor, and proposed the fitting formula of configuration of single conductor. Zhang xue-song [12] et al. established the form finding formula of single conductor considering bending stiffness, and studied the influence of conductor stiffness on seismic response of electrical equipment.

At present, the influence of bending stiffness and angle of hanger location points are usually neglected in the study of configuration function and mechanical properties of conductors, which is simplified as cable structure without bending stiffness. But the down lead line of UHV substation is different from that of general transmission line. It is vertically arranged in space. As shown in Fig. 1, the span L is short and the height H between the hanger location points is long. Different from large-span conductors, the configuration function and mechanical properties of the conductor in Fig. 1 can not be neglected due to the obvious shortening of line length. In this paper, the configuration function of the conductor considering bending stiffness is deduced, and the influence of hanging point angles on the line shape is discussed. On this basis, finite element models of single conductor are established, and their mechanical properties under wind load are analyzed in detail. It provides a theoretical basis for the design, operation, maintenance and installation of substation down lead conductors. All manuscripts must be in English, also the table and figure texts, otherwise we cannot publish your paper. Please keep a second copy of your manuscript in your office. When receiving the paper, we assume that the corresponding authors grant us the copyright to use the paper for the book or journal in question. Should authors use tables or figures from other Publications, they must ask the corresponding publishers to grant them the right to publish this material in their paper.

2. Configuration function of single conductor

2.1. Derivation of configuration function model

When considering the stiffness of a conductor, the conductor is subjected to both pressure and bending moment, and is no longer the form of catenary. At this time, both the axial force and the shear force are applied to the conductor section (as shown in Fig. 2). It is assumed that the gravity load per unit length of the conductor is $P_0=Ar$, $A$ is the cross-section area of the conductor, $r$ is the line density of the conductor, and it is distributed uniformly and continuously along the conductor.

According to the moment balance equation at point C of the element section in Fig. 2:

$$\sum M_e = (V \cos \theta - T \sin \theta)dx + (V \sin \theta + T \cos \theta)dy + M - P_0 dx \frac{dx}{2} - (M + dM) = 0 \quad (1)$$
According to the equilibrium, equation of direction X and Y among line AB, there are two equations:

\[ T_x = T \cos \theta + V \sin \theta \quad (2) \]

\[ T \sin \theta - V \cos \theta = R_A + P_x \quad (3) \]

Eq. 4 is available after taking Eq. 2 and Eq. 3 into Eq. 1:

\[ (R_A + P_0 x)dx + T_A dy - P_0 dx \frac{dx}{2} + dM = 0 \quad (4) \]

Eq. 5 can be obtained by eliminating the second order trace in Eq. 4 and finding the second derivative of \( x \):

\[ -P_0 + TA \frac{d^2y}{dx^2} = \frac{d^2M}{dx^2} \quad (5) \]

There is deflection differential equation of beams:

\[ \frac{d^2M}{dx^2} = EI \frac{d^4y}{dx^4} \quad (6) \]

By replacing Eq. 6 into Eq. 5, we can obtain the conductor ordinary differential equation with stiffness:

\[ \frac{d^4y}{dx^4} - \frac{T_A}{EI} \frac{d^2y}{dx^2} + \frac{P_0}{EI} = 0 \quad (7) \]

The horizontal component \( T_0 = T_A = T_D \) of arbitrary section can be obtained from external force balance in X-direction of the whole model. We assume that \( \frac{T_0}{EI} = K^2 \), The general solution of differential equation can be obtained after sorting out:

\[ y = \frac{C_1 e^{Kx}}{K^2} + \frac{C_2 e^{-Kx}}{K^2} + \frac{P_0}{2T_0} x^2 + C_3 x + C_4 \quad (8) \]

The four undetermined coefficients of the general solution are determined by the boundary conditions of the conductor, and it determines the constraint modes of the hanger location points. We can set up four boundary conditions to slove the four coefficients:

\[ y(0) = 0, \quad y'(0) = a, \quad y(L) = H, \quad y'(L) = b \quad (9) \]

Among them, L represents the span of the conductor, H represents the span between the hanger location points, and a and b represent the tangent value of the angle between the hanging point of the conductor and X direction. By offering different parameters of boundary conditions, we can obtain the actual line shapes of down lead conductor under different conditional parameters.

2.2. Case analysis

In order to verify the practicability of the conductor position function, this section makes a comparative analysis based on a practical case. In reference [11], the position coordinates and tension level of a single conductor in a substation are measured. In this section, a traverse model is established by using the position function of the conductor considering the bending stiffness. Based on the material parameters and boundary conditions in reference [11], the shape finding of the actual conductor is carried out. In
order to facilitate comparison, the curves fitted by actual measurement data of the conductor, the results of catenary shape finding and the results of shape finding presented in this paper are listed in Fig. 3.

In Fig. 3, it can be seen that the maximum sag of the model in this paper and the test curve are both 2.2 m. While the catenary model has a larger sag of 2.4 m due to the neglect of stiffness. It can be concluded that the model in this paper has higher accuracy and stronger applicability in form finding analysis of single conductor.

Figure 3. Position function relationships of three models.

3. Study on mechanical properties of single conductor

The mechanical properties of single conductor are significantly affected by the parameters of wire length, hanging point angle and span. In this section, finite element models are established by using the position function derived from the previous section. The influence of the angle of the lower hanging point A and the span L of the upper hanging point is emphatically studied.

3.1. Effect of the angle of hanging point A

Taking the practical case of the lead-down project of 75201 disconnector B-phase I bus connection in Bachu substation as an example, the lead-down model is JGQNLH55XX-700, and its basic parameters are shown in Table 1. Different hanging angles will lead to different linear shapes of the conductor (in Fig. 3.1). The top hanging point is generally led vertically. In this paper, the influence of the angle (the included Angle with the horizontal direction) on the force of a single conductor under seven different angle working conditions is analyzed. The configuration function solved by MATLAB is used as the geometric model, and the finite element model is established by ANSYS software. The whole model adopts BEAM188 unit, and both ends of the conductor adopts the fixed-end constraint. The default value of V10 was the design wind speed.

Table 1. Basic parameters of conductor.

| Unit weight | Span | Elevation difference | Modulus of elasticity | Design wind speed |
|-------------|------|----------------------|-----------------------|------------------|
| kg/km       | L/m  | H/m                  | /MPa                  | m/s              |
| 1927        | 4    | 12                   | 5.5×10^5              | 30               |

Table 2. Setting table of parameters for seven cases.

| case number | angle of lower hanging point | boundary condition α |
|-------------|------------------------------|----------------------|
| case 1      | 0°                           | 0.000                |
| case 2      | 15°                          | 0.268                |
| case 3      | 30°                          | 0.577                |
| case 4      | 45°                          | 1.000                |
| case 5      | 60°                          | 1.732                |
| case 6      | 75°                          | 3.732                |
| case 7      | 80°                          | 5.670                |
Figure 4. The configuration diagram of the conductor under seven cases with a length of 13.24m.

From Fig. 4, it can be seen that when the angle of the suspension point is larger, the suspension point is approaching more to vertical state, the conductor will have obvious reverse bending points, and different alignments will affect its mechanical performance. This paper considers the effect of four different line lengths on the mechanical properties of single conductor, and different line lengths also represent different rise-span ratio. Because of the inconsistent linear shape of each case, it is difficult to uniformly formulate the rise-span ratio, that is to say, the redundancy rate $\beta$ of the conductor is considered as a reference. The formula for redundancy rate $\beta$ is $\beta = (L - L_0)/L_0$, $L_0$ is the length of the wire, $L$ is the span. The rise-span ratios with the conductor length of 13.5 m, 13.24 m, 13 m and 12.8 m are 0.5, 0.4, 0.3 and 0.2, respectively. The redundancy rate is 6.8%, 4.7%, 2.8% and 1.2% respectively.

Figure 5. Tension $F_A$ of single conductor.  

According to Fig. 5 and Fig. 6, the hanging angle of the conductor directly affects the force exerted on the wire. When the angle is small, the lower suspension point A is under the action of tension caused by gravity. Under the wind load, the tension is further enhanced. With the increase of angle, the
component of self-weight in the direction of conductor axis is increasing and the hanging point is under pressure instead, so the self-weight can offset part of the tension caused by wind load and reduce the tension FA of hanging point A. What’s more, when the angle is small, it is controlled by the vertical shear force. When the angle is large, it is controlled by the horizontal shear force provided by wind load. Therefore, the bending moment will be reversed with the change of angle, and it also indicates that at a certain angle, the bending moment value will be small, which is controlled by the proportion of gravity and wind load. Therefore, the effect of tension and bending moment should be considered comprehensively in the actual installation, and horizontal suspension should be avoided as far as possible.

For the comparison of four kinds of wire lengths, according to Figs. 5 to 3, it can be clearly seen that the shorter the wire length is, the smaller redundancy rate β is, and the more sensitive the conductor is to external loads. This is also consistent with previous studies [7, 9]. When the wire length is shortened from 13.5m to 12.8m, the horizontal counter-force FX of the conductor increases by 47% and the vertical counter-force FY increases by 136%. It can be seen that, regardless of whether the bending stiffness of the conductor is taken into account or not, when the wire shape is close to straightening, the force on the suspension point of the conductor increases sharply. Therefore, in the design of conductor length, it is necessary to consider the redundancy rate of conductor reasonably, so as to avoid the damage of suspension connection equipment or terminal caused by the excessive tension due to the conductor length is too short.

3.2. Effect of the span L

Because the installation environment of the lead-down line is different in the actual field, the upper hanging point D of the lead-down line is not completely below the lower hanging point A, so the span L of the lead-down line has a certain range of variation. As shown in Fig. 7, this paper considers the stress analysis of single lead-down conductor with 2% redundancy rate under four different working conditions with a span interval of 0.5m and span from 2m to 4m. The relationship between the counter-force of the hanging points at different angles and the span of the conductor is shown in Fig. 8. As shown in Fig. 8, with the increase of span, the total tension FA of the conductor decreases gradually. With the increase of span, span-depth ratio increases, the horizontal tension FX of hanging point A increases, while the vertical tension FY decreases. Therefore, the force on the conductor can be estimated conservatively as the span-depth ratio is considered at the same redundancy rate, What’s more, in actual layout, we should pay attention to the size of redundancy rate, which could be a safety consideration in larger span.

![Figure 7. θ = 60 Configuration distribution](image1)

![Figure 8. Relation of hanging point A in span L](image2)
4. Conclusion
In this paper, the position function of conductor considering stiffness is proposed firstly. Then, the influence of different boundary conditions is studied, and the parameters of single conductor are analyzed. Finally, the following conclusions can be drawn as:

(1) By comparing with the fitting curve of measured data, the model considering stiffness can effectively simulate the configuration of single conductor.

(2) For the single conductor, the angles of the hanging points directly affect the line shape of the conductor. The change of tension and angle of the conductor is generally linear. The tension decreases by 32% from $0^\circ$ to $80^\circ$. The lowest hanging angle of $60^\circ$ is the best condition with a small tension and bending moment. And horizontal suspension should be avoided in actual suspension.

(3) Under the same redundancy rate, the tension of single conductor decreases with the increase of span-depth ratio. When designing and installing, it could be considered conservatively.

(4) When the redundancy rate of the conductor is small, the conductor is close to straight, and the tension of the conductor will increase sharply. In actual suspension, an appropriate redundancy rate should be considered.

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