Nonlinear Wind-Induced Response Analysis of Substation Down-Conductor System

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Abstract. Substation down conductor structure system is generally bundled conductor, and has the characteristics of small span, large height difference, short length and upper and lower connection. Substation lead-down accidents caused by strong wind often occurs. Down conductor accidents of substation caused by strong wind often occur. In order to study the nonlinear wind-induced response of the conductor under wind load, the AR model method is used to simulate the fluctuating wind load, and the modal analysis and nonlinear time history analysis of the wind-induced response of the flexible conductor system are carried out by using ANSYS software. The effects of aerodynamic damping, wind direction and Span-to-height ratio on wind-induced vibration response are studied. The analysis results show that the response of down conductor system has obvious non-Gaussian characteristics; Compared with the conventional horizontal long-span transmission lines, the natural frequency of down conductor is higher, the influence of aerodynamic damping is smaller, and the response wind-induced vibration coefficient is larger. The wind load in plane will lead to larger reaction response, and the wind load out of plane will lead to larger displacement response. The increase of Span-to-height ratio will lead to the increase of reaction response and the decrease of displacement response of the structure.

Keywords: Down conductor · Non-gaussian statistics · Wind-induced response

1 Introduction

The down conductor structure of UHV substation is a typical flexible conductor structure, which is usually a multi split flexible conductor with spacer. It has the characteristics of small span, large height difference, long and short line, up and down connection, and is very sensitive to wind load. There have been many researches on wind-induced vibration response of horizontal and long-span split conductor. For example, scholars have conducted modal analysis on the split conductor, which shows that the low-order natural frequency order of the large-span transmission conductor is in the order of 10^{-2}–10^{-1} [1–3]. Yu Yongshuai [4] and Wang Shuliang [5] obtained the relationship between the aerodynamic damping and the natural frequency of the structure, indicating that the aerodynamic damping has a greater impact on the wind-induced vibration

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response of the horizontal long-span transmission line, and the aerodynamic damping plays a dominant role compared with the structural damping [6, 7]. With the increase of wind speed, the aerodynamic damping can significantly reduce the wind-induced vibration response of the structure. Due to the short length of the down lead system in the substation, its natural frequency is significantly different from that of the horizontal long-span transmission line [8], and the modal analysis of the small-span split down lead is also few. Zhang Xuesong et al. Studied the low-order mode of the soft bus and its electrical equipment [9]. Therefore, it is necessary to analyze the wind-induced vibration response characteristics of the down lead flexible system.

In this paper, AR method [10] is used to simulate the fluctuating wind load, and ANSYS software is used to analyze the time history of the down lead system by time domain method [11, 12], so as to obtain the wind-induced vibration response of the structure under the wind load, which provides a reference for the wind load calculation of the down lead system of the substation.

2 Model Parameter

The down conductor of Aksu UHV substation is used for analysis. The down lead is of four bundled structure. The type of the down lead is JGQNRLH55XK-700, and the type of tubular bus is 6063G-T6-∅200/184. basic parameters is shown in Table 1. In this paper, combined with the example of Aksu substation down conductor project system, the model is established by ANSYS software, and the whole model adopts BEAM189 unit. the upper end of down conductor is consolidated, the lower end is coupled with the tubular bus, and the two ends of the tubular bus are consolidated.

Table 1. Parameter of the conductor

Category	M/kg/m	R1/R2/mm	E/MPa	L/m	H/m
Down conductor	1.927	41/51	5.5×105	2	16
Tubular bus	16.29	180/200	7.4×105	8	/

Where M is unit mass, R1 and R2 are inner diameter and outer diameter respectively. And E is young's modulus, L is span, H is height difference.

3 Simulation of Wind Load

In this paper, Davenport wind speed spectrum [13] is used to simulate the wind speed time history with randomness, time correlation and spatial correlation by using AR model under MATLAB workspace. The basic wind pressure is taken as 0.56 kN/m^2, the site category is B, the change of average wind speed along the height adopts exponential wind profile, and the wind speed profile index a is 0.15. See Table 2 for other main parameters.

Table 2. Parameters of simulated pulsating wind velocity time history

Surface roughness coefficient K	Stage frequency Hz	Simulation interval/s	Number	Sample time/s
0.00327	4	1/16	21	256

According to the location coordinates of down conductor, the wind speed time history of all coordinate points is simulated. Limited to the space, only part of the wind speed time history curves of node 1 and node 10 are listed in this paper (Fig. 1). It can be seen from Fig. 1 that the AR model method is in good agreement with the target power spectrum.

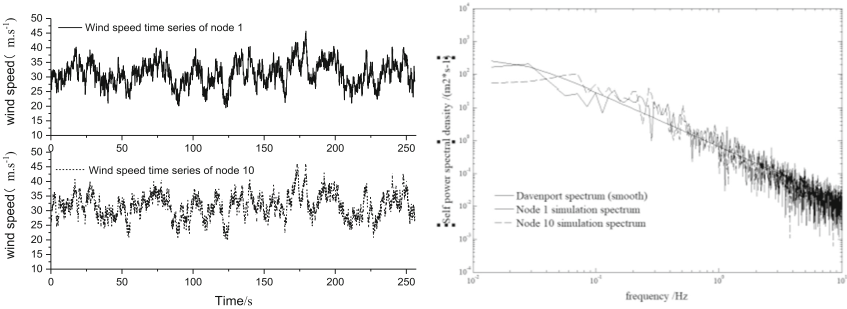


Fig. 1. Wind speed time-history curve and simulated wind spectrum

4 Dynamic Characteristic Analysis

The down conductor structure system of substation is generally four bundled conductor, which has the characteristics of small span, large height difference, long and short line, up and down connection. Before the dynamic time history analysis of the down conductor system, it is necessary to carry out modal analysis, the dynamic characteristics of the structure can be obtained after modal analysis. The main indexes include the natural frequency of the structure and the corresponding vibration mode. See Table 3 for the specific parameters. These indexes are important parameters for dynamics study.

As shown in the Fig. 2, Model 1 is the parameter four bundled down conductor model in this paper; model 2 is a single wire model with the same parameter; model 3 is a four bundled down conductor model with horizontal layout; model 4 is from literature [14], which is a single span equal height four bundled wire model with a span of 353 m (representing general long-span transmission wire).

In this paper, only the first four modes of the down conductor system are given, as shown in Fig. 3. In the figure, the first mode is the overall swing deformation along the yz plane of the down conductor; the second mode is swing deformation in the *xy* plane; the third mode is the torsion deformation along the y axis of the coupled system; the

Table 3. Natural frequencies of models

Frequency	First mode	Second mode	Third mode	Fourth mode
Model 1	1.925	2.584	4.183	5.182
Model 2	0.937	1.687	2.579	3.724
Model 3	1.769	4.066	4.112	5.212
Model 4 [14]	0.172	0.343	0.344	0.438

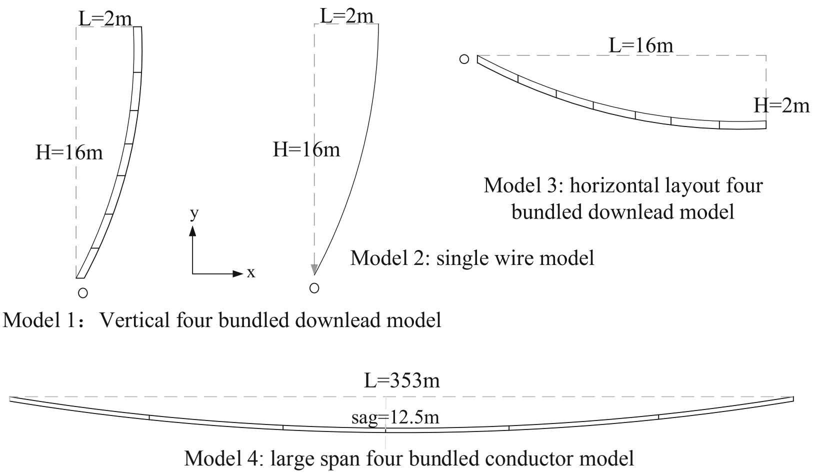


Fig. 2. Schematic layout of model 1 to model 4

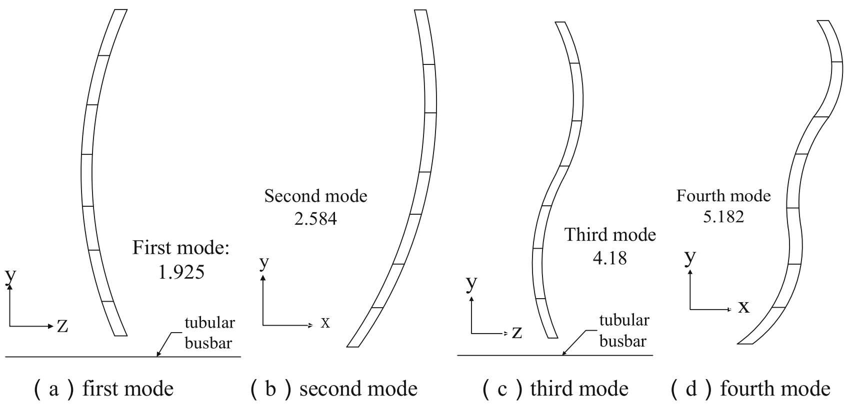


Fig. 3. The first four modes of Model 1

fourth mode is the double wave bending deformation in the *xy* plane, the performance of the first four modes is also related to the basic guide The linear modal form is consistent [4, 5].

It is worth noting that the vibration mode behavior of the down conductor model (model 1) in this paper is the same as that of model 3, and the natural frequency is also close. In addition to the second-order natural frequency, the average difference is 2.3%. Compared with model 4, the natural frequency of model 3 is one order of magnitude different. Literature [8] has studied the natural frequency of the suspension wire, and the natural frequency is mainly composed of span L and level under tension T control, when the span is small, the natural frequency of the conductor will obviously increase, which is basically consistent with the theory. And the average of the first four orders of model 1 is 1.6 times higher than that of the single conductor model 2. When the single conductor is extended to the four bundled conductor, T will also change significantly, which is also verified in reference [11]. The comparison of several models shows that the down lead system is different from the general large-span conductor, because of its short line length, small span but large height difference, its natural frequency is obviously different from that of the general large-span transmission line, and its natural frequency is large, so the dynamic response characteristics of them are also significantly different.

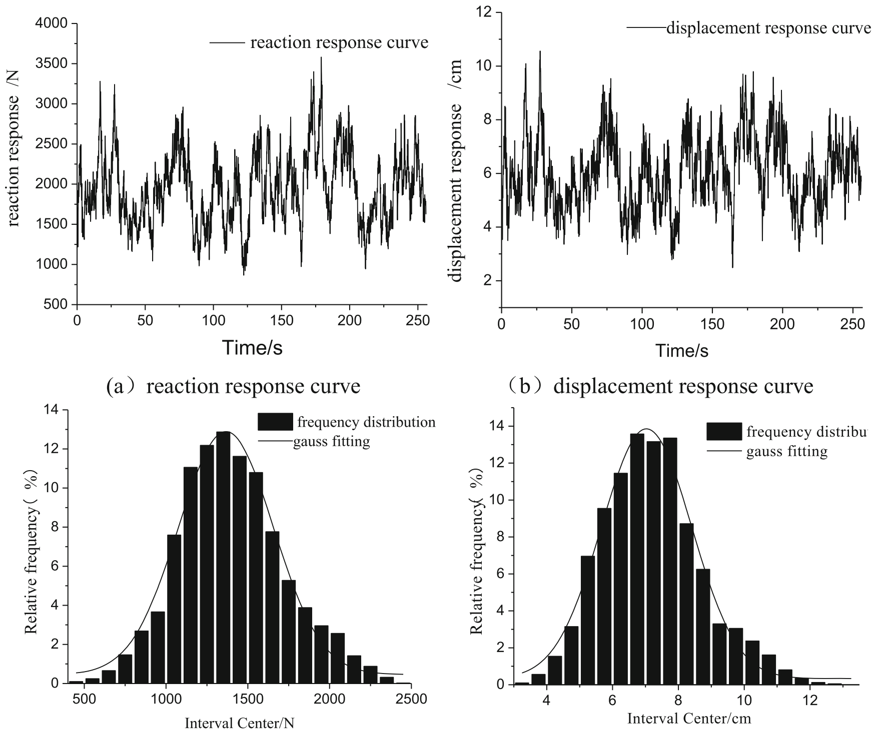
5 Parameter Analysis

Based on the dynamic characteristics of the four bundled down lead system, the wind speed V, the wind direction angle θ, and the aerodynamic damping ξ_a will affect the dynamic response of the structure. Therefore, the main three different parameters are set to study the influence of different parameters on the wind-induced vibration response of down conductor structure. For a highly nonlinear structural system, the response may show non-Gaussian distribution, such as some large-span membrane structures. Down lead system is also a typical nonlinear system, which will lead to the change of dynamic response characteristics and damping ratio. Therefore, this paper uses ANSYS software to carry out the finite element nonlinear time history analysis. The frequency distribution of its response is shown in Fig. 4. Its frequency distribution deviates from the Gaussian type. It is no longer applicable to directly use variance to express the dynamic performance of the response. Therefore, the maximum value of the response is directly used to represent the dynamic performance of the structure.

5.1 Influence of Aerodynamic Damping Ratio

In the wind-induced vibration response of long-span transmission lines, the aerodynamic damping of conductors is dominant relative to the structural damping, and the wind-induced vibration response of transmission lines will be overestimated without considering the aerodynamic damping [4, 5]. According to the aerodynamic damping formula (1) in reference [4], it can be seen that the aerodynamic damping is mainly affected by the wind speed V, the natural frequency f of the structure and the vibration mode.

$$\zeta_{ai} = \frac{\rho_a d C_D}{8\pi f_i m} V(1 + \cos^2 \phi) \tag{1}$$



（a）reaction response curve （b）displacement response curve

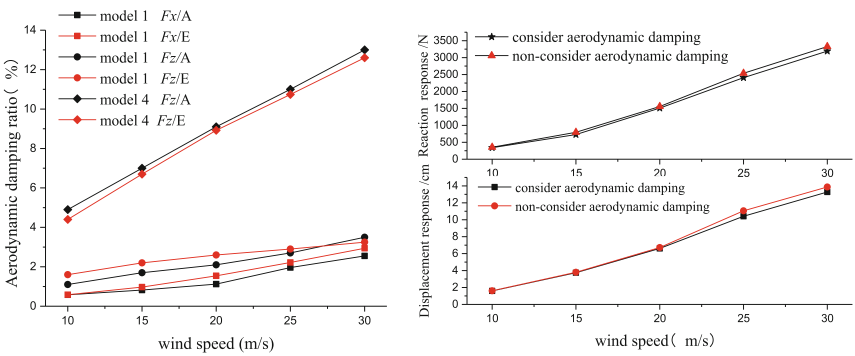
（c）reaction frequency distribution （d）displacement frequency distribution

Fig. 4. Response time history curve and frequency distribution of node 1

$$\phi = \begin{cases} \pi/2\text{-}\arctan(\overline{f}/mg) & \text{in-plane vibration mode} \\ \arctan(\overline{f}/mg) & \text{out-plane vibration mode} \end{cases} \quad (2)$$

C_D is the drag coefficient. In this paper, according to《Electrical Design of Electric Power Engineering Handbook》, the value is 1.2; air density ρ_a is 1.293 g/L; d is the diameter of a single wire, the value is 0.051m; m is the wire density of a single wire, the value is 1.972 kg/m; V is the average wind speed of the wire; f_i is the i-th order natural frequency of the model; and $\overline{f}$ is the average wind load acting on the unit length of the transmission wire.

For the down lead structure, compared with the general long-span transmission line, the first four order natural frequency of the down lead structure is larger, and the aerodynamic damping of the down lead structure is smaller than that of the long-span transmission line structure when other parameters are the same. It is suggested in reference [14] that the damping ratio of cable net structure should be 1%, and in reference [5] that the first four damping ratio of six bundled conductor vibration mode should be 0.97% to 1.64% through wind tunnel test, so the damping ratio of down-lead system structure in this paper should be $\xi_s = 1\%$. According to the literature [15], the main influence of the damping ratio is the resonance response. Through the calculation and analysis, the smaller the damping ratio is, the larger the proportion of the resonance response component is, and the larger the structural response amplitude is. The damping ratio has great influence on the structure with resonance response as the main response, but has little influence on the down lead flexible system with background response as the main response. In the wind-induced vibration response of conductor, the influence of aerodynamic damping ratio is greater. When calculating the aerodynamic damping ratio of the down conductor, the influence of aerodynamic damping is directly considered in the damping matrix: $\xi = \xi_s + \xi_a$. therefore, the aerodynamic damping ratio ξ_a under different wind speeds of the structure can be obtained by setting the damping matrix of different sizes to make its response consistent with that of the structure considering the aerodynamic damping. Through the above method, the aerodynamic damping ratios of model 1 and model 4 under different wind speeds are calculated and compared with formula (1). The specific results are shown in Fig. 5.



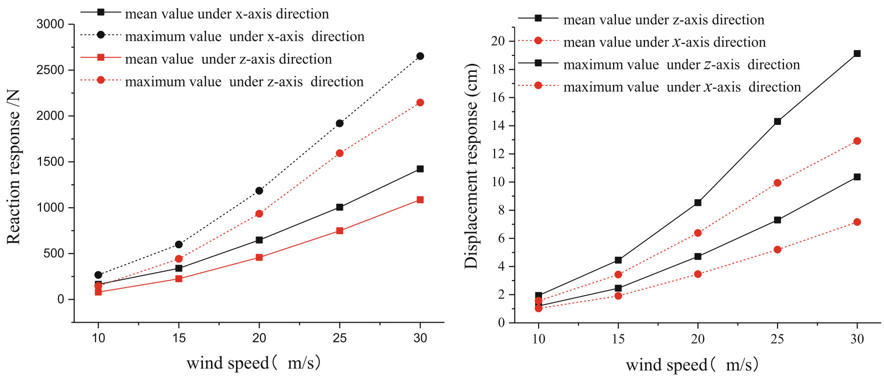
（a）comparison of aerodynamic damping ratio （b）comparison of model 1 responses

Fig. 5. Effect of aerodynamic damping on dynamic response of lead-down system

It can be seen from Fig. 5(a): the aerodynamic damping ratio calculated by ANSYS is relatively consistent with formula (1) (where: *Fz, Fx* is the direction of wind load, A is calculated by ANSYS, and E is calculated by formula (1)). It can be seen that the aerodynamic damping ratio of model 1 is significantly lower than that of model 4, that is, the aerodynamic damping of down conductor structure is smaller than that of large-span conductor; the aerodynamic damping under different wind directions is also different, the aerodynamic damping ratio out of plane is higher than that in plane, and the aerodynamic damping ratio out of plane is 40% higher than that in plane on average. Figure 5(b) shows the influence of the aerodynamic damping ratio on the response of model 1 in the plane. For the maximum reaction force of model 1, after considering the aerodynamic damping, the effect of aerodynamic damping is stronger with the increase of wind speed, and the difference is 5.3% with the wind speed of 30 m/s; for the maximum displacement response, the maximum difference is no more than 6%. The above results show that the wind-induced vibration response of the down lead system is different from that of the traditional horizontal long-span transmission line, and the aerodynamic damping has little influence on the wind-induced vibration response of the down lead system.

5.2 Influence of Wind Direction Angle

In Sect. 5.1, two wind direction angles of wind direction along *z* axis and wind direction along *z* axis are set to analyze the wind-induced vibration response of model 1. After considering the influence of aerodynamic damping, two groups of results under different wind speeds are shown in Fig. 6.



（a）Reaction response （b）Displacement response

Fig. 6. The influence of wind direction angle on wind-induced response of lead-down system

It can be seen from Fig. 6 that the response of the wind direction angle to the reaction force and displacement of the down conductor system are different: the displacement response of the structure under the z-axis wind direction angle is significantly higher than that under the *x*-axis wind direction angle, and the greater the difference between the two is with the increase of the wind speed, the average and maximum difference between them is 33.4% and 35.9%; for the reaction, the response under the *z*-axis wind direction angle is significantly lower than that under the *x*-axis wind direction angle. The difference between the mean value and the maximum value of the reaction under the action of the two is 41.5% and 58.1%. The difference between them lies in the modal distribution of the structural system and the influence of its own stiffness distribution. The down conductor system is distributed in the *x*-*y* plane as a whole, and its stiffness in the plane is significantly higher than that out of the plane. Under the x-axis wind force, it will lead to the "tension" of the down conductor, while under the *z*-axis wind force, it will not. Therefore, the displacement of the *z*-axis wind direction angle is larger, while the reaction force is smaller. In order to ensure the safety of down conductor structure, wind load of *x*-axis wind direction angle is adopted.

6 Conclusion

In this paper, through the simulation of fluctuating wind load, the analysis of dynamic characteristics of down conductor system and the dynamic time history response analysis of wind load, the following conclusions can be obtained:

(1) due to the high nonlinearity of the down conductor system, the wind-induced vibration response is obviously non-Gaussian, so it is no longer suitable to directly use the response variance to express the dynamic performance, Therefore, the maximum value of the response is directly used to represent the dynamic performance of the structure.
(2) for the wind-induced vibration response of the structure: because the length of the down lead structure is shorter than that of the previous large-span transmission line, and the natural frequency of the structure is larger, which also leads to the smaller aerodynamic damping of the down lead structure. the out of plane displacement response of the structure is larger under the out of plane wind force of the *z*-axis wind direction angle; while the in-plane reaction response of the *x*-axis wind direction angle is larger under the in-plane wind force.

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