Analysis of Wind-induced Response Limit State of Transmission Tower-line System

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***Abstract*— In order to understand the failure mode and limit state of transmission tower components in the wind-induced vibration damage stage, this paper takes a 220kV transmission line in Guangdong as the research object. Through the analysis of the failure path of main materials under different wind speeds and the collapse state of tower line system, the following conclusions are drawn: 1. Under the action of wind load, the collapse of transmission tower mainly occurs in the middle of the tower. The tower line system is the most sensitive at 90 °and the wind angle of 0 ° is the least sensitive. 2. Among the main members, the two ends of the main member supported by diaphragm and auxiliary member have weak restraint and the largest force, and yield first under load. 3. When the critical wind speed reaches 90 °wind direction, the transmission tower collapses fastest and the tower body collapses due to elastic-plastic instability.**

***Index Terms*— tower line system, dynamic analysis, failure path, collapse and failure**

I. Introduction

Transmission towers collapse in strong winds. The research on the dynamic failure mechanism of transmission tower line system under wind load is the theoretical basis for the wind resistant design of transmission tower line system, and also an important topic in the field of wind resistant research of transmission tower line system[1].

Hou Jingpeng et al. [2] used a cat-head transmission tower as a research object, simulated a wind speed sample using a matlab program, and used the B-R criterion to judge the structural instability, which verified the dynamic roll instability and failure of the structure under wind load. Jiang Zhicai [3] performed numerical simulation analysis on the example, and obtained the degradation law of the axial stiffness of some members, which has certain reference significance for further preventing the transmission tower instability and damage in engineering; Li Hongnan et al. [4-5] considered the structure The initial defects and the non-linearity of the geometric material affected the stability of the transmission tower under uneven ice-covered loads, wind loads, and ice-covered loads. The collapse of most transmission towers is due to the overall instability of the structure. The overall instability of the structure is often caused by the failure of local components, including strength failure and stability failure [6].

This paper establishes a finite element model of the tower line system, uses the harmonic synthesis method to simulate the pulsating wind speed time history, and calculates the wind load according to the height zone. The wind load time history is mainly applied to the structure, considering the geometric nonlinearity and material nonlinearity. Dynamic time history analysis, the dynamic response characteristics of the tower line system under the action of extreme wind loads are obtained. The Budiansky-Roth criterion is used to study the nonlinear stability of the transmission tower. By analyzing the failure types of the members, the failure mechanism of the transmission tower is studied, and some conclusions are helpful to the wind resistance design of the transmission tower.

II. Collapse Failure Criterion

A. Component Failure Judgment

In this article, the equivalent stress of the section of the member reaches the yield strength for the first time as the critical point of the member entering the yield. The ratio of the equivalent stress to the yield strength is the failure rate, and the failure rate is $\sigma_s / f_y \geq 1$ as the basis for judging the failure of the member. However, after the failure of the rod, it can continue to bear the load, and the force can be further increased, and more rods have gradually entered the yield, so there is a process of failure. When the wind speed increases to a certain level, the collapse occurs the tower was destroyed.

B. Failure Criterion Based on Finite Element Analysis

Literature [7] believes that with the increase of wind speed, the sudden wind speed caused by the displacement of the tower top is the destruction wind speed. Reference [8] considers that when the structure undergoes large deformation under small disturbances, it means that the structure is unstable or buckling occurs. For the transmission tower structure, the literature thinks that the tower top displacement increases suddenly, and the structure damage is judged when ANSYS does not converge.

The time history analysis method is used to simulate the dynamic response process of the transmission tower under the action of the wind field. When the transmission

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tower structure is damaged dynamically under wind load, the dynamic response of the structure will show the characteristics of divergence. At this time, the iterative non-linear dynamic equations will not converge. The left side of the equation is the bearing capacity of the structure, and the right side is the wind load. The equations do not converge, that is, the dynamic equations of the structure are not balanced, and the structure is damaged due to the inability to withstand the wind load. Therefore, in this paper, the structural bearing capacity and the wind load cannot maintain the balance, that is, the iteration of the equations does not converge as the collapse criterion, and the moment when the iteration does not converge is the failure of a part of the structure.

C. Budiansky-Roth Guidelines

The Budiansky-Roth criterion was first proposed by Budiansky and Roth [9] when studying the buckling problem of spherical shells. The criterion can be expressed as: if a structure causes a drastic response change under a small load increment, the structure is considered to buckle. This criterion is based on physical intuition and is relatively easy to implement in numerical calculations.

III. Engineering Overview and Finite Element Model

A. Project Overview

This article takes a 220kV transmission line in Guangdong as the research background, and selects one tower and two lines system as the research object. As shown in Fig. 1, the main height of the transmission tower N6 is h = 62.5m, and the uppermost layer of the transmission line is the ground line and the conductor 1. Conductor 2 and conductor 3 are double-split conductors. The conductor (ground) wire and the transmission tower are connected by overhang insulators. The lengths of the insulators of the ground wire and the conductors are 2.32m and 2.5m, respectively.

Yu Cong et al. [10] analyzed the failure process of the transmission tower line system for N6 under the effect of equivalent static wind load and found that the failure of the main materials of the transmission tower mainly occurred in the fifth to ninth paragraphs. Therefore, in order to facilitate the description of the failure analysis process of the main components and parts of the main materials, the main materials of the transmission tower are further divided. Fig. 1 shows the numbers of the fifth to ninth members.

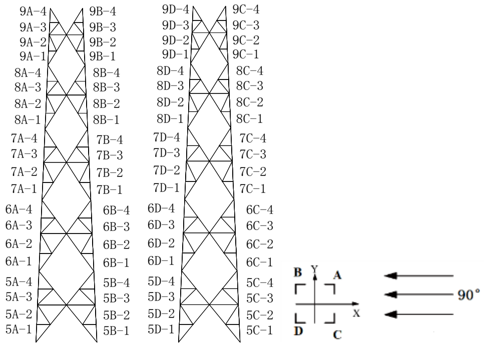


Figure 1. Schematic diagram of main material number

B. Establishment of Finite Element Model

(1) Transmission tower modeling: The BEAM188 unit is used to simulate the physical and mechanical properties of the transmission tower members. The bilinear follow-up strengthening model is adopted as the nonlinear constitutive model of steel. (2) Guide / ground line modeling: When modeling the guide / ground line, LINK180 rod unit is used for simulation. The constitutive model uses an ideal elastic model. (3) Insulator modeling: The LINK180 unit is still used for simulation, and the constitutive model adopts the ideal elastic model. The model is shown in Fig. 2.

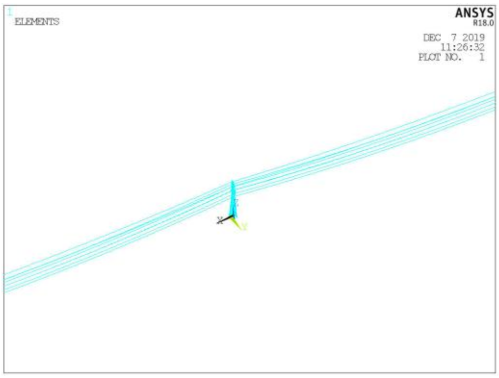
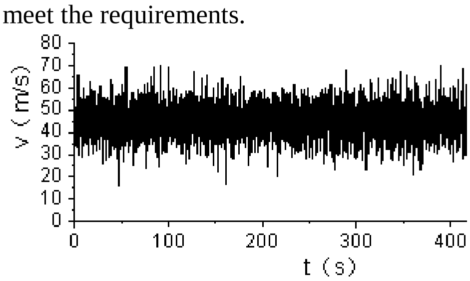


Figure 2. Two-line model of one tower

IV. Simulated Wind Load

A. Wind Load Time History Calculation

The Karman wind speed spectrum was used, and the upper harmonic synthesis method was used to simulate the wind speed time course [11], and the simulation time was 400s. A total of 12 simulation points along the height of the transmission tower are used as the simulated height of the wind load, and then the simulated wind load time history is applied to the nodes of the corresponding sections. Due to the existence of span, height difference and sag of the guide / ground line, each guide / ground line is divided into 10 wind speed zones, and the average height of each wind speed zone is taken as the wind speed simulated height of the segment and then converted into Wind loads are applied to all nodes corresponding to each segment. Figs. 3 and Figs. 4 show the pulsating wind speed time history curve when the height of the simulation point is 62.5m, and the comparison between the simulated wind pulse spectrum and the target wind spectrum. It can be seen that the simulated wind speed results meet the requirements.



Wind speed at the height of 62.5m at the top of the tower (V0 = 35m / s)

Figure 3. Simulated wind speed time history at the top of the tower

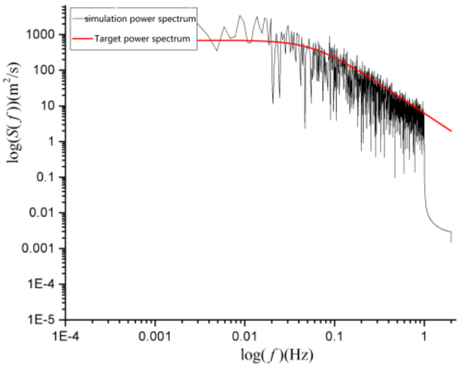


Figure 4. Comparison of simulated and theoretical values of power spectral density

B. Wind Load Simulation

Based on the quasi-stationary assumption, wind speed is converted to wind pressure and applied to the structure. The conversion of wind speed into wind pressure can be performed by Bernoulli's equation, as shown in equation (1).

$$\omega(t)=\frac{1}{2}\frac{\gamma}{g}v^2(t)=\frac{1}{1630}v^2(t) \quad (1)$$

Among them, ω (t) is the time history of wind pressure; γ is the bulk density of air; $g=9.8\mathrm{m/s}^2$ is the acceleration of gravity.

1) Wind load of transmission tower

For the tower structure, the calculation of wind load is shown in formula (2).

$$F(t)=\mu_s A_s \omega(t) \quad (2)$$

Among them, μs is the body shape coefficient; As is the windward area.

2) Wind load on power lines

For power lines, the wind load is calculated as shown in (3) below.

$$W_X(t)=\mu_{sc}ds\omega(t)\sin^2\theta \quad (3)$$

Among them: μ_{sc} is the size coefficient of the power transmission line;s is the length of the conductor between the simulated wind speed points of the ground wire; d is the diameter of the power line; θ is the angle between the wind direction and the direction of the power line.

C. Load Conditions

In order to simulate the ultimate state and inverted state of the tower, this article simulates the main material failure analysis of the tower line system under the 90 ° , 60 ° , 30 ° , and 0 ° wind direction angle conditions in Fig. 5, Based on the analysis of the equivalent static wind load of the tower line system in [11], the following conditions can be designed for the dynamic analysis according to the critical wind speed of instability, as shown in Table I. Low to high working conditions are used to simulate the collapse, so as to meet the requirements of this paper to analyze the working conditions of the transmission tower failure process.

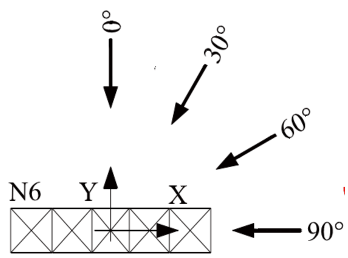


Figure 5. Wind direction angle diagram

TABLE I. TOWER-LINE SYSTEM LOAD CONDITIONS

direction	Wind speed（m/s）
90°	35、37.5、40、42
60°	40、43、44
30°	50、54、58、61
0°	55、60、65、69

V. ANALYSIS OF COLLAPSE OF TOWER LINE SYSTEM

A. Overall Stability Analysis of Tower Line System

According to the structural stability analysis criteria given above, from Table I and Fig. 6, it can be seen that the maximum value of the time-shift response is 0.175m when the average wind speed reaches 20m / s under the condition of 90 °wind direction, that is, the deformation exceeds the normal use limit When the average wind speed reaches 25m / s, the maximum displacement response is 0.574m, and it enters a severe damage state.

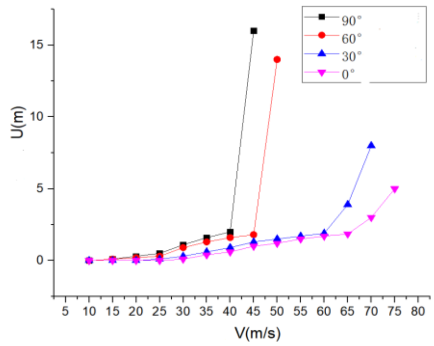


Figure 6. Wind speed and maximum displacement curves of towers of one tower and two-spans system model on different wind angles

When the average wind speed is increased from 40m / s to 45m / s, the tower top displacement increases dramatically, according to Budiansky-Roth According to the criterion, the overall instability of the structure has occurred, reaching the limit state of the bearing capacity. At the same time, the maximum displacement response of the structure is 8.652m, and the structure collapses and fails. Similarly, similar results can be obtained at other wind angles. When the transmission tower reaches the extreme wind speed, as long as there is a small increase in wind load, the displacement of the tower top will increase dramatically, the structure will be unstable overall, and the structure will respond to the maximum value, and the structure will collapse.

From the maximum displacement curve of the tower line model under different wind speeds at different wind direction angles in Fig. 6, the comparison of wind speed when the displacement is abrupt can be seen that the tower line system is most sensitive to wind load at 90 ° wind direction angle, and the least sensitive to 0 ° wind direction angle. sensitive. Therefore, in the structural design, the analysis of the failure path of the main material of the transmission tower under the 90 ° wind direction angle is of great significance to the stability analysis of the transmission tower.

B. Failure Path Analysis of Transmission Tower Main Materials

The failure paths of the main materials of the transmission towers at 90 °, 60 °, 30 °, and 0 ° wind direction angles are marked on the transmission line diagram, as shown in Fig. 7.

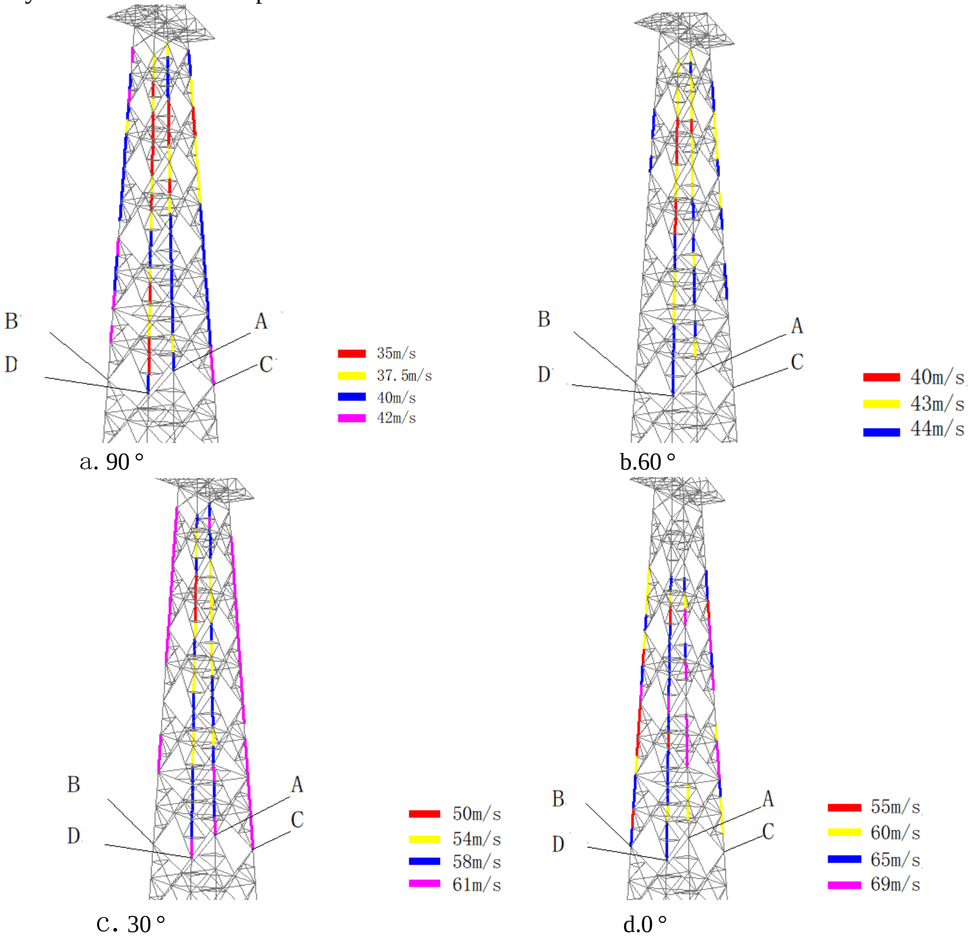


Figure 7. Failure path of main material of transmission tower under various wind direction angles

It can be seen from Fig. 7 that the first yielding at various wind directions is mainly concentrated in the seventh and eighth segments. When the damage is approaching, the main members of the eighth segment of the transmission tower almost all yield, and the bending of the seventh and eighth segments Almost all of the poles yielded, and the weak part of the transmission tower was the seventh and eighth sections. When all the members of this part failed, the transmission tower reached the critical bearing capacity and continued to increase the load. The transmission tower immediately collapsed.

From the beginning of the failure of some members to the near destruction of the transmission tower, the wind speed increased the least at a wind angle of 60 ° , because under this wind direction, the tensile and bending forces of the transmission tower were mainly concentrated on the A pole, and the bending and bending forces were mainly Concentrated on pole D, the failure is also mainly concentrated on these two main materials, so the load growth of the transmission tower after the failure of the pole member is lower than other wind direction angles, but because of the 60 ° wind direction angle, the transmission tower line system The load area is smaller than that at 90 ° wind direction angle, so the critical wind speed at 60 ° wind direction angle is still higher than that at 90 ° wind direction angle. The 90 ° wind direction angle of the tower line system is the most unfavorable wind direction angle. As the wind direction angle increases, the critical wind speed for collapse gradually decreases. This is because as the wind direction angle increases, the windshield area of the transmission line also increases, the transmission line vibration intensifies, and the tower-line coupling effect increases.

VI. Conclusion

This paper has obtained the following main conclusions by analyzing the limit state of transmission towers under different wind directions:

(1) Under 90 °, 60 °, and 30 ° wind direction angles, the tower's inverted tower damage occurred at the seventh and eighth sections of the tower, and the seventh and eighth sections are the weak parts of the transmission tower. However, at 0 ° wind direction angle, due to the restraint of the guide / ground wire, the position of the inverted tower of the transmission tower is moved down. Therefore, except for the upper part of the tower, the safety of the transmission tower should be monitored in the entire middle of the tower , Strengthen the members under greater force.

(2) In the main material members, the two ends of the main material members supported by the diaphragm and auxiliary materials are weakly restrained. Yield first occurs under the load, and the stress is redistributed after yielding. As the wind speed increases, the slope is inclined. The stress of the main member supported by the web member and the auxiliary member gradually increases and yields. Ultimately, the stress reaches the maximum and the failure occurs, and then the transmission tower collapses. Constraints can be strengthened by changing the arrangement of the diaphragm members.

(3) The leeward pressure bending rod has more yield area than the pulling bending rod, and the stress of the bending bending rod is greater than that of the pulling bending rod. Due to the coupling effect of the tower line system, at the critical wind speed of 90 ° wind direction angle, the collapse speed of the transmission tower is the fastest, followed by 60 ° and 30 ° wind direction angles, and the collapse speed at 0 ° wind direction angle is the slowest. Therefore, when designing the structure of the transmission tower, the influence between the transmission tower and the tower line cannot be ignored.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Li zhengkong is responsible for the overall project. The author Du Zifen is mainly responsible for the thesis writing and data sorting. The author Zeng Jing is mainly responsible for the experiment. The author Wang Zongkai is mainly responsible for the follow-up work of the paper.

References

[1] Y. Qiqi, “Wind-induced large-span transmission tower--the collapse of the line system,” 2016.

[2] H. Jingpeng, S. Zitang, W. Xinghong, Z. Yi, “Analysis of wind stability of transmission towers,” *Hydroelectric Energy Science*, vol. 29, no. 3, pp. 169-171, 2011.

[3] J. Zhicai, “Identification of the state of the tower after the instability and instability of the transmission tower,”Wuhan: Wuhan University of Technology, 2011.

[4] L. Qingwei, L. Hongnan, “Research on dynamic stability of transmission tower structure,” *Journal of Disaster Prevention and Mitigation Engineering*, vol. 28, no. 2, pp. 202-206, 2008.

[5] L. Xue, L. Hong-nan, H. Lian-zhuang, “Nonlinear buckling analysis of iced towers in high voltage transmission lines,” *Journal of Vibration and Shock*, vol. 28, no. 5, pp. 111-114, 2009.

[6] L. Hongnan, B. Haifeng, L. Hongnan, et al. “Current status and development trend of high-voltage transmission tower-line system disaster prevention research,” *China Civil Engineering Journal*, vol. 40, no. 2, pp. 39-46, 2007.

[7] Q. Fei, H. Zhou, X. Han, et al. “Structural health monitoring oriented stability and dynamic analysis of a long-span transmission tower-line system,” *Engineering Failure Analysis*, 2012, 20(none), pp. 80-87.

[8] Z. Mingzheng, “Static and dynamic response of high voltage transmission tower and tower line system,” Lanzhou University, 2014.

[9] R. Budianssky, “Axisymmetric dynamic buckling of clamped shallow spherical shells,” USA:National Aeronautics and Space Administration, 1962. pp. 597-606.

[10] Y. Cong, L. Zhengliang, W. Zhisong, “Analysis of failure process of transmission tower line system under equivalent static wind load,” *Special Structure*, vol. 161, no. 4, pp. 45-52, 2018.

[11] S. Wei, L. Bin, W. Yue et al. “POD-harmonic synthesis method for numerical simulation of pulsating wind field,” *Journal of Harbin Institute of Technology*, vol. 43, no. 12, pp. 13-17, 2011.

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