Transmission Tower Stress Analysis and Online Monitoring Scheme

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Abstract. So far, the theoretical study of the transmission tower line is not enough for the research and analysis of the transmission line under the wire icing and strong wind load. The understanding of the disaster load mechanism, structural analysis method and vibration control is still insufficient, resulting in the accidents of broken towers caused by ice coating, wind load and geological disasters still occur frequently, which is one of the main hazards of safe operation of power grids. First of this paper, the failure mechanism of transmission towers in various environments is studied in depth. Then, the mechanical characteristics of towers under environmental load are analyzed by finite element simulation results. Finally, an online monitoring method which is based on the mechanical characteristics of transmission tower, is proposed to detect the stress state and determine if there is a fault will occur or has occurred. Under these circumstances, the force of transmission towers will be known in real time, and power grid disaster can be prevented in advance.

Introduction

The high-voltage transmission tower is an important part of the transmission line and is the guarantee of normal power supply. However, as the transmission level increases, the height and width of the transmission tower are gradually increasing, which makes the ability of tower to resist disasters decline. Under the harsh environment of ice coating and strong wind load, it is more likely to cause a broken tower accident and extensive power outage accidents, which will have a serious impact on people's life and social production. When the wind load exceeds the design of the wind load of the tower, it will cause tower deflection and galloping of the wire. The tower is subjected to the continuous reciprocating pulling force brought by the wire dancing, which is easy to cause the tower to fall.

N. Prasad Rao and V. Kalyanaraman used the finite element software to carry out nonlinear analysis of the transmission tower, and found that the internal force of the tower structure is consistent with the experimental results[1]. Japanese scientists Shigehira Ozone et al. proposed two calculation models for solving the coupling system of the tower and the transmission line, derived the vibration frequency response function of the wire, and obtained the conclusion that the wire vibration has certain influence on the vibration of the tower [2].

In this paper, the failure mechanism of transmission towers under different environments is studied firstly, and the mechanical characteristics of the towers in failure are analyzed. The finite element software is used to simulate the force of the transmission tower under strong wind loads, and the mechanical characteristics are analyzed. Finally, the on-line monitoring method of the tower is proposed, and the mechanical characteristics of the tower are monitored in real time to prevent the accident of the tower collapse.

Mechanical Analysis of Transmission Line Tower

Scientifically, the force analysis of the tower is the problem of the structural strength and satisfies the basic equation of elastic mechanics. At present, there are two methods for analyzing the force
transmission tower. One is the traditional mechanical analysis. The bending moment and deflection of the transmission tower are calculated to check whether it is within the acceptable range. The other is to use the equivalent idea to make the tower equivalent to a single-ended beam model.

**Equivalent Beam Model**

In order to meet the universality of the tower modeling, the tower can be regarded as a variable-section cantilever beam model, and the dynamic characteristics of the tower under wind load can be studied.

Firstly, considering the function of the tower foundation, the tower is regarded as a simplified variable-section cantilever beam for analysis and research. Then, according to the relevant theory of variational method, the differential equation of the damped forced vibration of the variable section beam under wind load excitation is derived. The approximate analytical solution of the equation is solved by the averaging method in the nonlinear vibration theory. The stability of the steady solution is analyzed by the stability theory [3].

**Simulation Analysis of Transmission Tower under Wind Load**

The damage caused by the strong wind load on the transmission tower is the main cause of the tower accident. It is necessary to study and analyze the force of the tower under the wind load to solve such accidents. In this paper, the model of transmission tower is built with finite element method, considering wind load and the actual working condition of the transmission tower.

**Wind Characteristics Analysis**

According to the wind load of the tower, the wind load can be simplified to the average wind. The effect of the wind on the tower is mainly related to the wind speed and wind direction, so the average wind and wind speed profile are used to describe the average wind.

The average wind speed at a certain height is a random variable that varies with time. At a certain height, the probability of occurrence of different average wind speeds follows the Weibull distribution [4]:

$$p(\bar{v}, \alpha, \beta) = \frac{\alpha}{\beta} \left(\frac{\bar{v}}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{\bar{v}}{\beta}\right)^{\alpha}\right)$$

(1)

α and β in the formula are Weibull distribution parameters.

The different winds in the atmosphere have different average wind speeds at the same time. Davenport et al. obtained the formula of the exponential wind profile based on a large number of measured results [5].

$$\bar{U}(z) = U(z_{ref})\left(\frac{z}{z_{ref}}\right)^\alpha \quad \bar{U}(z) = U$$

(2)

Where $z_{ref}$ is the reference height, taking 10m; α is the ground roughness coefficient. According to the roughness of the ground, China divides it into four categories: A, B, C, and D. The corresponding ground roughness coefficient α is shown in the table 1.

| Types | Ground type                                      | α    |
|-------|-------------------------------------------------|------|
| A     | Offshore areas, islands, coasts, lakeshores and desert areas | 0.12 |
| B     | Fields, villages, jungles, towns and suburbs     | 0.16 |
| C     | Urban area of dense buildings                    | 0.22 |
| D     | Urban areas with dense buildings and high houses  | 0.30 |
Finite Element Simulation of Transmission Tower

Simulation was performed using ANSYS WORKBENCH. The Q345B steel is used to build a cat-head transmission tower with an elastic modulus of $2.1 \times 10^{11}$ Pa, a Poisson's ratio of 0.3 and a density of 11.85 g/cm$^3$. The tower is 20m high, with a maximum width of 11.2 m from the left to the right, and a maximum spacing of 2.25m.

Modal Analysis

The modal analysis of the transmission tower is carried out to investigate its deformation in the vertical direction. The modal analysis of the tower model is carried out by software to obtain the vibration frequency in each mode.

As depicted in Fig 1, the simulation results show that the resonant frequency of the transmission tower is very low, the first-order mode is 1.4328Hz, the second-order is 1.6923Hz, and the sixth-order modal frequency is only 2.5179Hz. Therefore, the transmission tower is prone to resonance at low frequencies, and the low-frequency resonance makes the tower deformation very serious, especially in the cross-arm suspension, the degree of deformation is the most serious, indicating that the cross-arm portion is the most vulnerable.

Forced Movement of the Tower under Wind Load

According to Table1, we choose the coefficient $\alpha$ equals to 0.16. In order to simplify the following simulation, the wind speeds in the vertical direction are discretized. The wind speed at a height of 10 meters from the ground is used as a reference to calculate the speeds at the height of 5m, 15m and 20m from the ground. Setting the wind speed at a height of 10 meters is 6m/s, 10m/s and 15m/s respectively to explore the impact of wind speed on the tower.

As shown in Figure 2, studies have shown that the influences of different wind speeds to the tower. Suppose the wind direction is forward wind, perpendicular to the front of the tower. The wind pressures at different wind speeds are calculated and applied to the tower to obtain the simulation results of the deformation of the tower at different wind speeds. At different wind speeds, the position that produces the greatest deformation is always in the position of the cross arm, followed by the cantilever on both sides of the cat head tower, and the deformation is also severe. This is because the position of the cross arm and the cantilever is relatively high, and the wind pressure is large. In addition, the structure of the cross-arm portion is the longest part of the transverse connection in the tower structure, resulting in a large force-bearing area under the action of the forward wind.

Because the tower is fixed, the windward structure of the tower will change due to the difference in wind direction, which in turn causes the tower to produce different deformations at the same wind speed. Through the simulation software, the wind direction and the front angle of the tower are explored at 0°, 45°, and 90°.

Fig 3(a) shows the deformation of tower caused by winds from 90° angle. When the wind blows...
from the direction of 90° to the front of the tower, the result of simulation shows that the maximum deformation of the tower can reach 15.25% of the maximum spacing. What’s more, the cantilever of the cat head tower lacks the structure of the longitudinal cross-connection of the sides, so the deformation degree of the structure is the most serious. The cross-shaped partial shape variable that is not directly subjected to wind pressure, and almost don’t deform.

Fig 3(b) shows the deformation of tower caused by winds from 45° angle. When the wind blows from the 45° angle to the tower, more tower structures are exposed to the wind pressure, causing the tower to withstand more forces. From the result of simulation, we can see that the deformation at cross arm and the cantilever are the most serious, reaching 46.7% of the maximum spacing of the tower. According to the decomposition of the force, the wind load will generate forces both in horizon and vertical aspects and make the tower deform seriously.

Through the simulation analysis of the wind direction, it can be judged that the tower will produce the largest deformation when the wind direction and the front side have an angle. The largest deformation part is the cross arm and the cantilever of the tower.

On-line Monitoring Scheme for Mechanical Characteristics of Transmission Tower

According to the modal analysis of the tower and the force deformation simulation under wind load, the resonance frequency of the cat-head transmission tower is very low. In the case of wind loads, the two positions of the crossbar and the cantilever of the tower are most susceptible to deformation. Considering the influence of wind direction on the tower, the maximum deformation caused by the horizontal wind direction on the front of the transmission tower is the smallest when the wind load is constant, the crossarm is still the most severely deformed part; the horizontal wind direction is 90° from the front of the tower. The maximum deformation occurs at the cantilever of the tower, and the deformation is higher than the wind direction of the front. When the angle between the wind direction and the front of the tower is 45°, the maximum deformation produced by the tower is much higher than the first two directions. This shows that the tower is most susceptible to wind loads when the wind direction is at an angle to the front.

The tower will produce a more pronounced deformation under wind load, so a stress sensor can
be installed on the tower to monitor the strain of the tower. When the stress is higher than the safety threshold, the deformation of the tower is very serious, and it needs urgent response. From the simulation results, the cross-arm and cantilever of the cat-head tower are the most vulnerable and the most prone to deformation, so these two positions are the best position for detecting stress and the most important position. Since the resonant frequency of the tower is very low, resonance is also a factor that threatens the safety of the tower. A sensor for detecting the vibration frequency is required to monitor whether the tower is at the resonance frequency. In addition, under strong wind loads, a slight rotation will occur. Therefore, an angular velocity sensor can be installed on the front and side of the tower to detect the rotation of the tower and monitor the state of the tower. Fig 4 shows specific program for monitoring mechanical properties. In Fig 4, $a$ is the stress sensor, $b$ is the vibration sensor and $c$ is the angular velocity sensor.

**Summary**

This paper starts from the cause of the broken tower accident in the transmission tower, analyzes the stress of the tower under the ice and strong wind loads, and simulates the situation that the transmission tower is in strong wind load, for different wind speeds and different wind directions. The impact was explored and found that the crossbar and cantilever of the tower were the most easily deformed parts, and severe deformation occurred when the wind direction was at an angle to the front of the transmission tower. At the end of the paper, based on the conclusion of the simulation, a scheme for monitoring the mechanical properties of the tower is proposed to ensure the safety of the tower.

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**References**

[1] N. Prasad Rao. V Kalyanaraman. Nonlinear behavior of lattice panel of angle towers. J. Journal of constructional Steel Research, 57 (2011), 1337-1357.

[2] Ozono S, Maeda J. In-plane dynamic interaction between a tower and conductors as lower frequencier. J. Engineering Structures, 14 (1992), 210-216.

[3] Wei Zhang. Vibration Analysis of Transmission Line Tower Structure. D. Harbin Institute of Technology. (2011).

[4] Xinde He. Wind Engineering and Industrial Aerodynamics. Beijing National Defense Publishing House. (2006).

[5] Davenport A G. The dependence of wind load upon meteorological parameter. R. In proceedings of the international research seminar on wind effects on building and structures. University of Toronto Press, Toronto. (1968).