Impact Analysis of Wind Direction upon Wind Load on Tower Line in Mountainous Microtopography

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Abstract. When transmission lines pass through microtopographic area, the acceleration effect of wind speed should be taken into consideration during designing. However, the acceleration ratio coefficient of wind speed should not be selected simply according to mountain slope as specified by standards. In order to comprehensively consider the impact of wind direction and microtopography upon acceleration ratio of wind speed. This paper selects the acceleration ratios of wind speed at the height of 10m-120m in a tower position at 24 angles of direction wind by virtue of CFD simulation analysis. Combined with the line trend, this paper compares and calculates the change rule of wind loads on tower body and lead/ground wires after considering the pre/post-impact of acceleration ratio of wind speed. Through analysis, this paper forms suggestions on wind-resistant design for lead/ground wires in transmission lines in microtopographic area as well as accident analysis for reference.

Key words: Transmission lines; wind direction; acceleration ratio of wind speed; microtopography; CFD

1. Introduction

There is an obvious acceleration effect of wind speed in the mountainous microtopographic wind field; as a result, numerous tower collapse accidents have been caused by wind through transmission lines [1]. According to the regulations on transmission lines in China, the design wind speed should be 10% higher than that of in plain area when there is no meteorological observation data available in mountainous area. However, the regulations do not take into account the impact of wind direction on the relative position relation with microtopography. In fact, the acceleration ratio of wind speed from different incoming wind directions is significantly different in the complex mountainous area [3]. Subject to capital and time constraints, it is difficult to obtain the design wind speed in the microtopographic area through actual measurement in wind field [4]. The simulation of area size may be easily limited by the cross-section size of wind tunnel test by means of determining microtopographic wind field characteristics through wind tunnel test [5]. As the mileage of transmission lines extends long and the transmission lines distributed within dozens of kilometers may often need a larger range of wind field to be analyzed, therefore lots of wind tunnel tests may be required to determine the wind field characteristics along the entire transmission lines. At present,
alternative methods generally adopted at home and abroad refer to: through establishment of mountainous terrain model, obtaining information such as acceleration ratio of wind speed and distribution of wind speed along height by virtue of CFD simulation analysis [6-8]. Through comparative analysis of wind field in deep-cut valley, Li Yongle [9] studied the change characteristics of wind speed in bridge site along vertical direction and along main beam direction and determined the ratio relationship between the wind speed in bridge floor and the gradient wind speed in different angles of attack. Through building a single three-dimensional hill model, Li Zhengliang [10] calculated the mountainous acceleration effect; discussed the impact of factors such as mountain slope, height and geomorphology on the acceleration ratio of wind speed; adopted the numerical simulation method to obtain the distribution law of acceleration ratio of wind speed at different sites of mountaintop and hillside; and fitted the modified algorithm of acceleration ratio calculation based on the analysis data.

Zhou Zhiyong [11] evaluated the impact of grid modeling method and calculation parameter setting on the characteristics of complex mountainous wind field, and proposed the partition of flow field grid by using non-uniform grid, which could reduce grid demands and ensure grid partition quality. Jiang Chuanzhong [12] studied the eastern main island of Nan’ao Island in Guangdong Province, simulated the wind field around the terrain from different incoming directions under the actual terrain conditions, and analyzed the impact of angle of direction wind on flow field characteristics. Deng Yuanchang [13] analyzed the impact of surface vegetation roughness on the calculation accuracy of CFD simulation wind field, and suggested the roughness value.

During bridge construction and wind energy development [14], a large number of CFD simulation studies have been carried out for the mountainous microtopographic wind field, which provides a feasible way to obtain the characteristics of mountainous wind field and design parameters of transmission lines. Based on the above research results, this paper carries out the simulation analysis of complex microtopographic flow field and obtains the corresponding relation between wind direction and acceleration ratio of wind speed; meanwhile combined with direction of transmission lines, it further analyzes the impact of complex topography on the wind load of transmission lines.

2. Grid Division in Flow Field for Simulation Analysis

2.1. Surface Modeling

The research object of microtopography is the location of transmission lines in the first mountain range offshore Fujian coast. Use Google Earth to obtain elevation data of topography undersurface, take samples spaced by 30m and totally obtain 43,381 discrete elevation points, and import the discrete elevation points into the reverse engineering software Global mapper to fit the four-terraced terrain surface. The surface 3D modeling is shown in Figure 1. Spaced by 15°, select 24 angles of direction wind for CFD simulation analysis, and line trend is 48° north by east. Figure 2 shows the spatial position relation among tower position, line trend, and angle of direction wind.
2.2. Grid Division in Space Flow Field
The surface 3D model is poured into the grid division platform ICEM to form the computation domain. The mountain surface is divided by triangular grid. During generation of volume grid, the boundary layer grid in transition section is firstly generated on the outer boundary surface of the mountain, and a structured spatial grid is then generated from the transition section to the outermost layer of flow domain in the computation domain. The grid size is gradually increased from inside to outside. The inflow boundary of solution domain is 2,000 meters high and 15,000 meters wide. In the computation domain, the upstream length is 7,500 meters and the downstream length is 9,500 meters. The volume grid in the space flow field adopts the mixed grid and the total units of volume grid are 2.83 million. Figure 3 shows the finally divided mountainous local grid and full computation domain grid.
2.3. Boundary Condition Setting in Flow Field

(1) Entrance conditions: The entrance adopts speed entrance boundary conditions of wind field in atmospheric boundary layer. The UDF (user-defined functions) programming is adopted to realize wind speed profile, turbulence kinetic energy $k$, and turbulent dissipation rate $\varepsilon$.

The average wind speed with height below 400m is expressed in exponential form as follows:

$$V_z = V_0 \left( \frac{z}{10} \right)^\alpha$$  \hspace{1cm} (1)

In which, $V_0 = 10\text{m/s}$, $\alpha = 0.12$. The wind speed with height above 400m is consistent with that of at 400m.

For turbulent characteristics, adopt the turbulence intensity formula of physiognomy of Class III as suggested by Japan if the wind speed has the height below 400m:

$$I(z) = 0.1(z/H)^{0.06-\alpha} = 0.1(z/350)^{0.05-0.16}$$  \hspace{1cm} (2)

For the numerical wind tunnel, $k - \varepsilon$ model calculates the transport equation between turbulence kinetic energy $k$ and turbulent dissipation rate $\varepsilon$. Therefore, the above turbulence intensity and integral scale needs conversion. The conversion relationship between the two can be expressed as:

$$k = \frac{3}{2} (V z I_z)^2$$  \hspace{1cm} (3)

$$\varepsilon = C_\mu^{1/4} \frac{k^{1/2}}{L_z}$$  \hspace{1cm} (4)

In which, $V_z$ is calculated as per Formula (1) $C_\mu = 0.09$. The turbulence integral scale adopts the formula $L_z = 100(z/30)^{0.5}$ suggested by Japan. The turbulence characteristics above 400m are consistent with those of at 400m.

(2) Boundary conditions on the top and both sides: Symmetrical boundary conditions (symmetry) are adopted on the top and sides of the basin.

(3) Outlet boundary conditions: Flow field outlet adopts pressure outlet boundary conditions.

(4) Mountain surface boundary conditions: There is no slip wall condition on the mountain surface, and rough wall surface is introduced on the ground for correction.

2.4. Solver Control

Adopt Fluent-3D double-precision implicit separation solver to calculate. The dispersion of convection terms adopts the second order windward format. The speed pressure coupling adopts SIMPLE algorithm. The convergence criterion of iteration is less than that of relative iteration residues of all control equations. Meanwhile the surface pressure coefficients are not changed through monitoring, the flow field is considered to be in steady state and the flow field results are extracted.

3. Research of Regularity of Acceleration Ratio of Wind Speed in True Wind Field

3.1. Change Regularity of Acceleration Ratio of Wind Speed with Wind Direction

Through simulation analysis, the wind speed from about 93 heights is obtained from 24 angles of direction wind above lower mountain surface up to 1650m. Based on Formula (5), the acceleration ratio of wind speed $\eta_z$ is obtained for the tower position in different angles of direction wind. As the
The height of the transmission tower is often below 120m, thus this paper only selects the acceleration ratio of wind speed from 10m to 120m for research.

\[ \eta_z = \frac{V_{\text{tower}}(z)}{V_{\text{inlet}}(z)} \]  

In which, \( V_{\text{tower}}(z) \) refers to the average wind speed when the ground clearance of the tower position is at \( z \) meanwhile \( V_{\text{inlet}}(z) \) refers to the average wind speed when the ground clearance of the inflow profile is at \( z \).

Figure 4 shows the changing curve of acceleration ratio of wind speed with angle of direction wind within height of 10m-120m in the simulated tower position.

**Figure 4.** Changing Curve of Acceleration Ratio of Wind Speed with Angle of Direction Wind within Height of 10m-120m

Based on Figure 4: (1) for the simulated tower position, the acceleration ratios of wind speed at each height are all larger than 1 within the angles of direction wind of 30°-270°. The acceleration ratios of wind speed at height of 10m reaches reach 1.694, 1.717 and 1.64 in the angles of direction wind of 210°, 195° and 180°. Within the angles of direction wind with significant acceleration effects of wind speed, the wind speed has the maximum acceleration amplitude at the height of 10m. As the height of ground clearance increases, the acceleration ratio of wind speed constantly decreases. (2) Within the angles of direction wind of 270°-0°-30°, most of the acceleration ratios of wind speed are less than 1, which indicates that the wind speed at the lower tower position of the angles of direction wind is heavily obstructed. However, as the ground clearance is increased, the acceleration ratio of wind speed is recovering, which indicates that the effect of mountain barrier is decreased with the increase of ground clearance.

Figure 5 shows the contour map of wind speed in whole basin at the heights of 10m and 120m in the angle of direction wind of 195°. Figure 5 shows that in the angle of direction wind of 195°, the tower position is within the wind speed contour at windward side of 16m/s.
Figure 5. Contour Map of Wind Speed at Angle of Direction Wind of 195°

Figure 6 shows the contour map of wind speed in whole basin at the heights of 10m and 120m in the angle of direction wind of 0°. Based on Figure 6, in the angle of direction wind of 0°, the tower position at 10m high is within the wind speed contour at leeward side of 4m/s, meanwhile the tower position at 120m height is within the wind speed contour at 8m/s, which is consistent with the weakening mountain barrier impact as shown in Figure 4.

Figure 6. Contour Map of Wind Speed at Angle of Direction Wind of 0°

3.2. Values of Acceleration Ratio of Wind Speed under Angle Wind Effects

Force calculation is needed for gale conditions at included angles of 0°, 45°, 60° and 90° with the lines when transmission lines are designed. According to the line trend mentioned in this paper, the angle of direction wind with significant effects of acceleration ratio of wind speed is also considered, the data of acceleration ratios of wind speed at angles of direction wind of 225°, 195°, 165° and 135° are finally selected to correct height variation coefficient of wind pressure. Table 1 shows the values of
acceleration ratios of wind speed at 4 angles of direction wind corresponding to angle wind conditions in designing transmission lines.

Table 1. Values of Acceleration Ratios of Wind Speed at Angle Wind Conditions in Transmission Lines

| Angle of direction wind (°) | 135 | 165 | 195 | 225 |
|-----------------------------|-----|-----|-----|-----|
| Angle wind in corresponding line (°) | 90 | 60 | 45 | 0 |
| Height (m) | 10 | 1.15 | 1.505 | 1.717 | 1.512 |
| | 30 | 1.142 | 1.433 | 1.624 | 1.447 |
| | 50 | 1.134 | 1.38 | 1.555 | 1.403 |
| | 70 | 1.126 × 1.343 | 1.505 | 1.375 |
| | 90 | 1.118 × 1.318 | 1.468 | 1.359 |
| | 120 | 1.108 × 1.294 | 1.43 | 1.347 |

4. Wind Load Analysis of Tower Line in Transmission Lines

4.1. Calculation Rules of Wind Load in Transmission Lines

The standard values $W_{aw}$ and $W_{bw}$ of wind load in front and lateral tower are calculated according to Formula (5). The wind load of tower is generally divided according to wind pressure, which is calculated by analysis program of iron tower, and the parameters are detailed in Section 10.1.18 of Reference 2.

$$W_{aw} = W_0 \cdot \mu_z \cdot A_{aw} \cdot \beta_z$$
$$W_{bw} = W_0 \cdot \mu_z \cdot A_{bw} \cdot \beta_z$$

(6)

The standard value of ground wind load is calculated according to Formula (6). The wind load of lead/ground wires is usually calculated by the calculation form of electrical load. The parameters in the Formula are detailed in Section 10.1.19 of Reference 2.

$$W_s = \alpha_s \cdot W_0 \cdot \mu_z \cdot \beta_s \cdot d \cdot L_p \cdot \sin^2 \theta$$

(7)

Considering the angle wind effect of transmission lines and actual wind direction, the wind load of the tower and lead/ground wires under the angle wind effects is calculated respectively according to Table 2.

Table 2. Wind Load Calculation of Transmission Lines under Angle Wind Effects

| Angle wind $\theta$ (°) | Wind load of lead/ground wires | Wind load of tower |
|-------------------------|-------------------------------|-------------------|
|                         | $W_{aw}$                      | $W_{bw}$          | $W_{aw}$ | $W_{bw}$ |
| 0                       | 0                             | 0.25$W_s$         | 0        | $W_{aw}$ |
| 45                      | $0.5W_s$                      | $0.15W_s$         | $K_i \times 0.424 \times (W_{aw} + W_{aw})$ | $K_i \times 0.424 \times (W_{aw} + W_{aw})$ |
| 60                      | $0.75W_s$                     | 0                 | $(0.747W_{aw} + 0.249W_{aw})$ | $(0.431W_{aw} + 0.144W_{aw})$ |
| 90                      | $W_s$                         | 0                 | $W_{aw}$ | 0 |

Note: The single-angle steel $K_i$ takes 1.0 and the combined angle steel takes 1.1.
4.2. Analysis of Impact of Acceleration Ratio of Wind Speed upon Angle Wind Load
The arc height of pole tower in the tower position is 33m and the overall height of 45.5m. The actual horizontal span of the wire is 663m and the vertical span is 936m. The lead wire model is LGJ-400/35 and the ground wire model is GJ-80. The design wind speed is 31.3m/s.

This paper carries out two comparisons in order to analyze the impact of acceleration ratio of wind speed upon the angle wind load. Firstly, only the design wind speed is increased by 10% at 10m high according to the treatment methods for wind load in conventionally microtopographic area, namely, the basic wind pressure is increased to 1.21 times of the basic wind pressure in plain area. Secondly, according to the acceleration ratios of wind speed at angles of direction wind obtained from simulation analysis, the height variation coefficient of wind pressure is corrected, considering transmission line tower and wind load of lead/ground wires impacted by acceleration ratio of wind speed. If calculated by the second method, the Formulas (5) and (6) are changed to:

\[
W_{s,a} = W_0 \cdot \eta_s \cdot \mu_s \cdot A_{s,a} \cdot B_s \cdot A_{s,b} \cdot \beta_s
\]

\[
W_{s,b} = W_0 \cdot \eta_s \cdot \mu_s \cdot A_{s,b} \cdot B_s \cdot A_{s,a} \cdot \beta_s
\]

\[
W_s = \alpha_s \cdot W_0 \cdot \eta_s \cdot \mu_s \cdot \mu_w \cdot \beta_s \cdot B_s \cdot d \cdot L_p \cdot \sin^2 \theta
\]

When the wind load is calculated, the basic wind pressure is calculated according to the wind speed of 20m/s. \( \mu_i \) is calculated according to coastal landform of the Island, i.e. wind profile of Class A. \( \mu_{s,a}, \mu_{s,b}, A_{s,a} \) and \( A_{s,b} \) are calculated according to the information corresponding to wind pressure section given in the design document of the tower. \( B_s = 1.1, \beta_s = 1.5, \alpha_s = 1, \mu_w = 1.1, \beta_s = 1, \) and \( B_i = 1.1; \) wire \( d \) is 26.82mm, ground wire \( d \) is 11.5mm, and \( L_p \) is 663m.

According to the above settings of comparison calculation parameters, the wind loads of tower body and lead/ground wires in 4 angles of direction wind are obtained by two calculation methods. After correction of simulation analysis, \( K_{ts} \) and \( K_{ty} \) are defined as the difference coefficient of wind load on tower body in front side between the wind load on tower body and the specified 1.1 times of wind pressure after correction. After correction of simulation analysis, \( \kappa_c \) is defined as the difference coefficient of wind load on ground wire between the wind load on ground wire and the specified 1.1 times of wind pressure after correction. Figure 7 shows the changing curve of \( K_{ts} \) and \( K_{ty} \) with height at different angles of direction wind meanwhile Figure 8 shows the changing curve of \( \kappa_c \) with angle of direction wind.

![Figure 7. Difference Coefficient Curve of Wind Load on Tower Body](image1)

![Figure 8. Schematic Diagram of Angle Wind in Transmission Lines](image2)
Based on Figure 7, Figure 8, and acceleration ratio of wind speed in Table 1, it can be seen that: (1) the increase of wind loads on tower body and lead/ground wires mainly depends on the increase of acceleration ratio of wind speed at the corresponding angle of direction wind, meanwhile the line trend impacts the wind load very slightly; (2) at most of the angles of direction wind, the wind loads of the analyzed objects of iron tower and lead/ground wires are larger than the design wind load obtained from the specified 1.1 times of basic wind pressure; (3) with the increase of ground clearance, the acceleration ratio of wind speed obtained from simulation analysis is gradually decreased, which causes the difference between the wind load on tower head and the specified wind load to be constantly decreased;(4) at most of the angles of direction wind, the increasing range of wind load on lead/ground wires is ground wire < upper wire < small wire, which shows the rule that the acceleration ratio of wind speed gradually decreases as the height increases.

5. Conclusion
Through simulation analysis, this paper obtains the microtopographic wind field characteristics around the tower position of transmission lines, analyzes the change rule of the acceleration ratio of wind speed at the tower position with height and angle of direction wind, and comprehensively considers the impact of line trend upon the wind load of tower line in transmission lines. Through analysis, the main conclusions are stated as follows:

(1) This paper studies that the larger acceleration ratio of wind speed occurs under the condition of more than half of angles of direction wind when the iron tower is in the single ridge among mountains. The acceleration ratio of wind speed at 10m high at 195° of angle of direction wind reaches 1.717, which exceeds the regulated and suggested 1.1. For the similar topographic environment, it is recommended to avoid the windward side in the locally predominant wind direction and adjust it to the leeward side in the predominant wind direction.

(2) The line trend very slightly impacts the wind loads on tower body and lead/ground wires after considering acceleration ratio of wind speed. It is not necessary to consider changing the line trend to reduce the impact of microtopographic acceleration effects when engineering routes are selected.

(3) The acceleration ratio of wind speed gradually decreases as height increases. Under this impact, the increase amplitude of wind loads on tower body and lead/ground wires is also decreasing. Under the premise that the design safety margin of main material is consistent, the tower materials are prone to early breakage if they are closer to ground. The research results can be used as reference in case of analyzing the similar field accident of tower collapse by wind in microtopographic area.

Acknowledgments
This work has been funded by the State Grid Corporation of China (Project name: High Resolution Wind Field Characteristics Study on Mountainous Terrain by Adaptive Simulation Technology), and the financial aid number is GCB17201600017. The authors would like to thank the sponsor of State Grid Corporation of China.

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