Research on windage yaw characteristics of high-voltage insulators in complex wind field

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Abstract. In this paper, in order to fully consider the influence of complex wind field on the windage yaw angle of insulator string, the WRF-Fluent multi-scale calculation model is developed to simulate a windage yaw accident caused by a typhoon transit process in the Ouhai District of Zhejiang, China, the dynamic response of the faulty insulator string in the wind field is analysed through two-way fluid-structure interaction calculation, and the windage yaw condition of the insulator is obtained by transient dynamics simulation. The theoretical windage yaw angle under complex wind field is also calculated according to the design standard. This paper shows that the complex wind field has a nonnegligible influence on windage yaw angle of insulator string, so it is necessary to fully consider the influence of complex wind field on high-voltage insulators in future design standard.

1. Introduction

Insulators are an important part of high-voltage transmission line. Under the influence of environmental wind field, the insulator strings on the transmission tower will swing by the action of ambient wind force. It is prone to the situation that the windage yaw angle of insulator is too large, which will cause a reduction of air gap between the conducting wire hanging on the lower end of the insulator string and the transmission tower, it may leads to a transmission line trip accident. Specially, the windage yaw discharge accident of insulators in mountainous areas occurs frequently these years[1,2]. Researches has shown that the transmission lines erected in the coastal mountainous areas will suffer a wind speed mutation during the typhoon process, the complex terrain and special weather condition together will form a complex wind field, which will has a significant impact on the windage yaw of insulators in the transmission line.

However, the research on safety margin correction of high-voltage insulator in complex wind field is rare at present[3,4,5], the multiscale nesting method is rarely used in the research of windage yaw of insulator string. Therefore, based on a windage yaw accident of a transmission line, this paper researched the windage yaw characteristics of insulators by considering the local mountainous terrain and coastal typhoon meteorological conditions, and compared the theoretical windage yaw angle in the design specification with the simulation result.
2. Windage yaw calculation of the faulty insulator

2.1. Establishment of the insulator model

The composite insulator string FXBW-500/210 is used in the accident transmission line, and the technical parameters are shown in Table 1.

| Type       | Piece number of insulators | Shed diameter | Shed spacing | Structure height | String length |
|------------|-----------------------------|---------------|--------------|------------------|---------------|
| FXBW-500/210 | 32                          | 282/225(mm)   | 100(mm)     | 4450 ± 50(mm)    | 4450(mm)     |

According to the actual shape and size, the simplified rigid rod model is established based on the purpose of the research. Firstly, the windward area of the actual insulator string is considered, and then the size of the main body of the insulator string is considered.

The formula that calculates the windward area of FXBW-500/210 insulator string is [6]:

\[ S = n_1 n_2 A \]  

Where \( A \) is the windward area of each piece of insulator, \( n_1 \) is the number of insulator string for one phase, \( n_2 \) is the number of pieces of every insulator string, the windward area of metal fittings on the string equals to one piece of insulator. According to the parameter in Table 1, it can be obtained that the wind area of this type of insulator string is 0.86m².

The main stressed part of the insulator string is the mandrel between the metal fittings at both ends, which is covered with sheds, according to the shed spacing data in Table 1, it can be obtained that the length of insulator string’s sheds is 3.1m.

Based on the above data, the size of the simplified rigid rod model in this research is: 3.1m in length and 0.6m in diameter.

2.2. Establishment of the complex terrain

Firstly, a large scale topographic grid data with a spatial resolution of 30 meters is obtained from the Chinese Geospatial Data Cloud, which used for the land surface reverse modelling. Then the deviation is calculated and adjusted. Finally, the terrain size is cut to 7km × 3km, the complex terrain surface obtained by fitting is shown in Figure 1.

![Figure 1. Terrain fitting results.](image)

2.3. Establishment of the complex wind field

In this study, a mesoscale meteorological research and prediction format WRF model is used to simulate the passage process of the typhoon when the windage yaw accident occurs. The dynamic
framework of WRF mode adopts fully compressible and non-static mode, the horizontal computing
domain adopts Arakawa-C grid points, and the vertical direction adopts terrain-following mass
coordinates. In terms of time integration, the 3rd or 4th order Runge-Kutta algorithm is
adopted[7,8,9,10]. The kinetic equation, thermodynamic energy equation and the continuity equation
are as bellowed [11]:

\[
\begin{align*}
\frac{\partial U}{\partial t} + (V \cdot \nabla U) + \frac{\partial}{\partial y} (p, \phi) &= F_U \tag{2} \\
\frac{\partial V}{\partial t} + (V \cdot \nabla V) + \frac{\partial}{\partial y} (p, \phi) &= F_V \tag{3} \\
\frac{\partial W}{\partial t} + (V \cdot \nabla W) - g(\partial_\eta p - \mu) &= F_W \tag{4} \\
\frac{\partial}{\partial t} (\nabla \cdot \mathbf{V}) + \nabla \cdot (\nabla \cdot \mathbf{V}) &= 0 \tag{5} \\
\frac{\partial}{\partial t} \mu + (\nabla \cdot \mathbf{V}) &= 0 \tag{6} \\
\frac{\partial}{\partial t} \phi + \mu^{-1} [(V \cdot \nabla \phi) - gW] &= 0 \tag{7}
\end{align*}
\]

Where \( \mu \) is the quality of air per unit area in the model domain at \((x, y)\), the vertical coordinate
axis denoted as \( \eta \), \( \Theta \) is the momentum of the potential temperature field, \( \theta \) is the potential
temperature, \((u, v, w)\) are three dimensional covariance velocities, \( V = (U, V, W) \) represents
the moments of three dimension velocity field. \( p \) is the atmospheric pressure, \( g \) is the gravitational
acceleration, geopotential height \( \phi = gz \). \( F_U \) represents the forced term caused by the physical process,
\( F_V \) represents the forced term caused by the perturbation mixture, \( F_W \) represents the forced term
caued by the spherical projection, \( F_\Theta \) represents the forced term caused by the rotation of the earth.

In this paper, by importing the basic data of local terrain and obtaining the weather reanalysis data
during the night of the accident, 3 layers of calculation areas that centered on the accident area is
nested, as shown in Figure 2. The horizontal grid precision are 9km, 3km and 1km from the outside to
the inside respectively. The vertical height is divided into 50 layers. The simulation time is set to 4
hours before and after the accident, which is 8 hours in total.

![Figure 2. Nesting of calculation areas.](image)

![Figure 3. Near-surface wind velocity distribution in the innermost nested layer.](image)

The distribution of near-ground wind speed in the innermost nested layer at a certain time is
obtained by simulation, as shown in Figure 3. In this layer, the red part is the high wind speed zone,
which is the hilly area where the accident happened. It indicates that WRF model has a good
description of local wind speed surge in hilly terrain. The wind speed data of the innermost layer is
extracted as boundary condition of the Fluent simulation.
2.4. WRF-Fluent multiscale computation

Based on the terrain generated by reverse modeling and the insulator string model, the fluid-structure interaction model of the accident area is established, as shown in Figure 4. The terrain size is much bigger compared with the insulator string, in order to improve the speed of numerical calculation, a layer of nesting is created. According to the actual working condition of the insulator string, three directions of translational freedom at the top of the insulator string are limited. The vertical section of inlet wind speed \( v_x \) that obtained from WRF model is input into Fluent through UDFs, as the initialization condition of the entrance boundary, as shown in Figure 5.

![Figure 4. Windage yaw calculation model of the insulator string.](image)

![Figure 5. The section of inlet wind speed obtained from WRF model.](image)

The two-way fluid-structure interaction calculation between insulator string and flow field is carried out to obtain the distribution of wind speed in the flow field and the variation of the windage yaw angle of the insulator. The continuity equation and momentum conservation equation satisfied by the flow field are shown in the Formula 8 and 9:

\[
\nabla \mathbf{u} = 0
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \frac{1}{Re} \Delta \mathbf{u}
\]  

Where \( \mathbf{u} \) is the velocity of the air, \( p \) is the pressure, \( Re \) is Reynolds number. Transient calculation of the flow field is carried out using \( k - \varepsilon \) two equation turbulence model, equation \( k \) and equation \( \varepsilon \) are as follows:

\[
\frac{dk}{dt} = \frac{\partial}{\partial x_i} \left[ \left( v + \frac{v_i}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k - \varepsilon
\]

\[
\frac{d\varepsilon}{dt} = \frac{\partial}{\partial x_i} \left[ \frac{(v + \frac{v_i}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_i}}{\sigma_\varepsilon} \right] + G_\varepsilon \frac{\varepsilon}{k} - C_{2k} \frac{\varepsilon^3}{K}
\]

Where \( k, \varepsilon, \nu \) are turbulent kinetic energy, turbulent kinetic energy dissipation rate and laminar dynamic viscosity coefficient respectively, \( C_{1k}, C_{2k} \) are empirical constants, \( \sigma_k, \sigma_\varepsilon \) are corresponding Prandtl numbers of \( k \) and \( \varepsilon \), \( G_k \) is the generation term of turbulent kinetic energy caused by average velocity gradient.

3. Simulation and calculation results

3.1. Flow field calculation results

The flow field conditions in the calculation results are analysed. The height of the insulator string is about 60m above the ground, so the wind speed distribution at 60m above the ground is extracted from the calculation results of the flow field, as shown in Figure 6. The influence of mountain terrain on the
The wind field can be clearly seen: under the condition of the same height above the ground, local wind speed surge and wind direction change are generated on the windward slope, while on the leeward side, a low wind speed zone is formed.

Then analyse the flow field around the insulator. In the simulation results of the flow field, the wind speed time history curve in front of the suspension point of the insulator is obtained, and the section with relatively higher wind speed is shown in Figure 7. It can be seen that the wind speed change in front of the insulator conforms to the pulsation characteristics of natural wind, and the extreme velocity value in this period of time is 28.3 m/s.

3.2. Simulation results of the windage yaw of insulator string

In this paper, the windage yaw condition of insulator string is analysed by transient dynamics. The results show that in the flow field, the insulator string swings freely around the hanging point on the top, takes its two main swing directions to obtain the windage yaw angle that changing with time, as shown in Figure 8 and Figure 9. It can be seen that the insulator string performs like an approximate simple pendulum motion in the windward direction with the equilibrium position of about 50°, and in the crosswind side with the equilibrium position of 0°. The maximum windage angle are 69.1° and 63.9° respectively.

3.3. Calculation of theoretical windage yaw Angle

Currently, there are two widely used methods for windage yaw angle calculation of insulators which are string polygon calculation method and rigid body static calculation method[12]. The appropriate method is selected according to the research needs and the accuracy requirements of calculation. In this paper, on the basis of the rigid body straight bar model and without considering the influence of wires, the theoretical windage yaw angle of the insulators is calculated as follows:
\[
\gamma = \arctan \left( \frac{G_H}{G_V} \right) \tag{12}
\]

Where \(G_H\), \(G_V\) are respectively the wind load and the gravity load at the centroid of the insulator string. According to the design manual [6], wind load of insulator string is calculated by Formula 13, while gravity load is calculated by Formula 14:

\[
G_H = 9.81 C \frac{v^2}{16} \tag{13}
\]

\[
G_V = mg \tag{14}
\]

Where \(v\) is the designed average wind speed, here, the maximum wind speed \(v_{\text{max}} = 28.3\text{m/s}\) that obtained from the simulation results is put into the formula. \(C\) is the total windward area of insulator string, when the diameter of the insulator string is less than 254mm, the windward area of each piece is 0.02m², for the large shed and double shed, the windward area is 0.03m².

Table 2. Comparison of the windage yaw angle.

| Maximum windage yaw angle (theory) | Maximum windage yaw angle (simulation) | Error between theory and simulation |
|-----------------------------------|---------------------------------------|-----------------------------------|
| 64°                               | 69°                                   | 7.3%                              |

4. Conclusions

In this paper, the windage yaw angle of insulator string in the complex wind field is obtained by two-way fluid-structure interaction simulation, and the theoretical result is calculated to make a comparison with the simulation result. It can be seen from Table 2 that under the consideration of local complex wind field, the actual windage yaw angle of insulator string is 7.3% larger than the theoretical windage yaw angle. It is proved that since the current windage yaw design standard of insulator string does not fully consider the influence of complex terrrain and special meteorological conditions, the actual wind speed that some insulator strings suffer may exceed the designed wind speed, so further quantitative research is needed on windage yaw characteristics of high-voltage insulators in complex wind field. It also shows that the WRF-Fluent multi-scale calculation method has the capacity and convenience to calculate the dynamic response of insulator string in complex wind field.

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