Study on Transient Wind Field Model of Transmission Line Based on Multivariable Harmonic Superposition Method

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Abstract. The wind deflection angle is directly related to the electric gap and the construction cost of the transmission line, so the accuracy of the wind deflection calculation method and the reasonable value of the relevant parameters are very important for the safe operation and economic rationality of the transmission line. Because of not considering the effect of wind speed fluctuation and thunderstorm impact wind and other adverse weather conditions, the calculation of wind deviation is often unsafe. In this paper, the multi variable harmonic superposition method is used to establish the transient wind field model under strong wind and thunderstorm blast weather conditions, considering the temporal and spatial correlation characteristics of wind field. On this basis, the distribution model of fluctuating wind load acting on the transmission line is constructed, which provides the basis for the subsequent wind deflection calculation of transmission line.

1. Introduction
Transmission tower is an important facility of power grid system. As the skeleton of supporting transmission line, transmission tower often suffers from failure or even collapse in extreme cases. The causes of transmission tower damage and tower collapse are different. The main influencing factors are the different load conditions and sizes, and the wind load often plays a controlling role in tower design. In view of the transmission line in coastal landform, it is of great theoretical and engineering significance to comprehensively understand and master the static and dynamic characteristics of transmission tower under various loads of typhoon wind field, and to study the wind-induced response characteristics of tower line coupling system, so as to improve the security of power grid in coastal areas [1-2].

The wind deflection angle is directly related to the electric gap and the construction cost of the transmission line, so the accuracy of the wind deflection calculation method and the reasonable value of the relevant parameters are very important for the safe operation and economic rationality of the transmission line. At present, only an empirical wind pressure non-uniformity coefficient is used in the design code of transmission line to consider the reduction of wind load caused by the spatial correlation of wind speed, and the static calculation of wind deflection is carried out by using the simple pendulum model. The accuracy of the results needs to be discussed. Because of not considering the effect of wind speed fluctuation and severe weather conditions such as thunderstorm, the
calculated value of wind deflection is often not safe for design, which is one of the main reasons for frequent wind deflection accidents[3].

The multi variable harmonic superposition method is used to establish the transient wind field model under strong wind and thunderstorm blast weather conditions, considering the temporal and spatial correlation characteristics of wind field in this paper. On this basis, the distribution model of fluctuating wind load acting on the transmission line is constructed, which provides the basis for the subsequent wind deflection calculation of transmission line[4-5].

Because the transmission line is a kind of nonlinear structure, when using Newmark-β time domain analysis method to analyze the wind deviation, it is necessary to obtain the wind speed time history of each spatial position on the transmission line. The wind speed at each location can be expressed as follows:

$$U_j(t) = \bar{U}_j + \tilde{U}_j(t)$$  \hspace{1cm} (1)

Where $\tilde{U}_j(t)$ is the fluctuating wind speed at the position of conductor $j$, which is generated by the one-dimensional multivariable harmonic superposition method with high accuracy. $\bar{U}_j$ is the average wind speed at the position of conductor $j$, which can be calculated according to the exponential law as follows:

$$U(z) = \bar{U}_{10} \left( \frac{z}{z_{10}} \right)^{\alpha}$$  \hspace{1cm} (2)

Among them, the average wind speed at 10m height is determined according to the code for transmission line design; the ground roughness index under class B landform is 0.15.

2. Principle of harmonic superposition method

The power spectrum of fluctuating wind speed describes the distribution of fluctuating wind energy in frequency domain, and reflects the contribution of different frequency components in fluctuating wind to turbulent fluctuating total kinetic energy. It can be divided into two categories according to whether the turbulence integral scale varies with height or not. For example, Davenport spectrum, Harris spectrum and so on are adopted in Chinese codes. The other is to consider the change with height, such as Kaimal spectrum, von Karman spectrum and so on. Kaimal spectrum has the following form:

$$\frac{f S_u(z, \omega)}{u_x^2} = \frac{200x}{(1+50x)^{5/3}}$$  \hspace{1cm} (3)

$$\sigma_v = [\beta u_x^2]^{1/2}$$  \hspace{1cm} (4)

Here, $x = \frac{f z}{U_x}$, $z$ are the height, $f$ is the frequency, $\omega$ is the circular frequency, $\beta$ is the dimensionless constant related to the terrain. Table 1 lists the $\beta$ values corresponding to different roughness length $z_0$ obtained by a large number of actual measurements.

| $z_0 / m$ | 0.005 | 0.07 | 0.30 | 1.00 | 2.50 |
|----------|-------|------|------|------|------|
| $\beta$  | 6.5   | 6.0  | 5.25 | 4.85 | 4.00 |

Based on the simulated value of fluctuating wind speed, its root mean square and other statistical characteristics may not be consistent with the theoretical turbulence profile. Therefore, it is necessary to modify the Kaimal spectrum according to the variation characteristics of atmospheric turbulence along the height in the region where the structure is located. The relationship between turbulence intensity $I_z$ and wind spectrum is as follows:
 Combined with equation (3) and equation (4), considering the turbulence intensity and wind speed profile along the height, the wind spectrum correction factor $Q_z$ can be defined as:

$$Q_z = \frac{(I_z U_z)}{\int_0^\infty S(\omega) d\omega}$$  \hspace{1cm} (7)

Where $I_z$ is the theoretical value of turbulence profile given by the code. The modified Kaimal spectrum can be expressed as follows:

$$S(z, \omega) = Q_z S(z, \omega)$$  \hspace{1cm} (8)

Now consider a group of $N$ one-dimensional stochastic processes $v_j(t)$ ($j = 1, 2, \cdots, n$), then the cross spectral density matrix is:

$$S_{\omega} = \begin{bmatrix} S_{11}(\omega) & S_{12}(\omega) & \cdots & S_{1n}(\omega) \\ S_{21}(\omega) & S_{22}(\omega) & \cdots & S_{2n}(\omega) \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1}(\omega) & S_{n2}(\omega) & \cdots & S_{nn}(\omega) \end{bmatrix}$$  \hspace{1cm} (9)

Here, $\omega$ is the circular frequency and $S_{ii}(\omega)$ on the diagonal is the self-power spectrum. $S_{ij}(\omega)$ on the non-diagonal line is the cross power spectrum function, which represents the power spectrum of the same direction and different points. The expression is as follows:

$$S_{ij}(\omega) = \sqrt{S_{ii}(\omega) S_{jj}(\omega)} \sqrt{Coh(\omega)} e^{i \phi(\omega)}$$  \hspace{1cm} (10)

Here, the value of $COH(\omega)$ adopts the spatial correlation function of wind field recommended by Davenport:

$$Coh(\omega) = \exp \left\{ -\frac{\omega^*}{\pi} \frac{\sqrt{C_x^2 (x_i - x_j)^2 + C_y^2 (y_i - y_j)^2 + C_z^2 (z_i - z_j)^2}}{v_i + v_j} \right\}$$  \hspace{1cm} (11)

Here, $C_x = 16$, $C_y = 6$, $C_z = 10$.

* $\phi(\omega)$ in equation (10) is the phase difference between two points in space.

* $\omega^* = 2\alpha (z_i - z_j) / (v_i + v_j)$

* By Cholesky decomposition of $S(\omega)$, the following results can be obtained.

$$S(\omega) = H(\omega) H^T(\omega)$$  \hspace{1cm} (13)

Here, $H(\omega)$ is a matrix:

$$H(\omega) = \begin{bmatrix} H_{11}(\omega) & 0 & \cdots & 0 \\ H_{21}(\omega) & H_{22}(\omega) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ H_{n1}(\omega) & H_{n2}(\omega) & \cdots & H_{nn}(\omega) \end{bmatrix}$$  \hspace{1cm} (14)
$H(\omega)$ is the lower triangular matrix and $H^*(\omega)^T$ is the conjugate transposition matrix of $H(\omega)$.

3. Transient wind field model of transmission line

According to Shinozuka theory, the wind speed field of one-dimensional multivariable fluctuation can be simulated by the following formula:

$$V_j(y_j, z_j, t) = \sqrt{2(\Delta \omega)} \sum_{m=1}^{N} \sum_{n=1}^{N_j} H_{mn}(\omega_m) \cos(\omega_m t - \theta_{mn}(\omega_m) + \phi_{ml})$$

Here,

$$\theta_{mn}(ml) = \tan^{-1}\left(\frac{\text{Im}[H_{mn}(\omega)]}{\text{Re}[H_{mn}(\omega)]}\right)$$

(16)

$\theta_{ml}$ is an independent phase angle uniformly distributed between 0 and $2\pi$.

When the number of simulation points is large, the application of this superposition method will cost a lot of time. Therefore, the introduction of fast Fourier transform (FFT) technology can greatly improve the calculation efficiency. $M$ is the number of segments in the time domain, $M = \frac{2\pi}{\Delta \omega \Delta t}$, thus changing the wind speed time history form into:

$$V_j(p\Delta t) = \sqrt{2\Delta \omega} \text{Re}\left\{G_j(p\Delta t) \exp\left[i\left(\frac{p\pi}{M}\right)\right]\right\}$$

(17)

Here, $p=0,1, \ldots, M-1$ and $j=1,2,\ldots,n$. $G_j(p\Delta t)$ is given by:

$$G_j(p\Delta t) = \sum_{l=0}^{M-1} B_j(l\Delta \omega) \exp\left(i\frac{2\pi lp}{M}\right)$$

(18)

Here,

$$B_j(l\Delta \omega) = \sum_{m=1}^{L} H_{jm}(l\Delta \omega) \exp(i\phi_{ml})$$

(19)

Figure 1 shows the time history curve of wind speed at the hanging point of suspension insulator of transmission line accident tower after considering pulsation. It is worth mentioning that in order to eliminate the impact amplification effect of sudden load, the linear growth process of wind speed from 0 to average value is added in the first 100 s of wind speed time history. Figure 2 shows the comparison between the target value and the simulated value of the power spectrum of fluctuating wind speed. It can be found that the target value of wind power spectrum is in good agreement with the simulation value, indicating that the obtained wind speed time history can effectively reflect the distribution characteristics of fluctuating wind speed energy in frequency domain.

Figure 1. Wind speed at suspension point of transmission line.
Figure 2. Wind spectrum simulation.

Figure 3 and Figure 4 show the comparison between the simulated and theoretical values of turbulence intensity. It can be seen from the figure that the wind speed simulated by the modified Kaimal spectrum can better reflect the variation of turbulence intensity along the height.

Figure 3. Variation of turbulence intensity along the height of ground wire.

Figure 4. Variation of turbulence intensity along the height of transmission line.

4. Conclusion
A transient wind field model under strong wind and thunderstorm blast is established by using the multivariable harmonic superposition method and considering the temporal and spatial correlation characteristics of wind field in this paper. The distribution model of fluctuating wind load acting on the transmission line is obtained by using the modified Kaimal spectrum simulation. It can better
reflect the variation law of turbulence intensity along the height of wind field, and can be used to analyze the wind deviation of transmission line effectively.

References

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