A Review on the Deviation of High Voltage Transmission Lines Caused by Wind

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Abstract. In China, with the development of high voltage, long distance transmission line surge in demand, meeting the requirements of the insulator string length is also increasing, which lead to frequent occurrence of wind partial flashover accidents, and this is a serious threat to the safe and stable operation of power systems. Therefore, it is very significant to study the wind deviation problem of high voltage overhead transmission line.

In this paper, to study the problem of wind deflection of high voltage overhead transmission lines, a large number of documents have been collected. At first, the calculation method of the wind deviation model and the wind deflection angle of the insulator string is introduced. Then, according to the stress analysis of the insulator string hanging point, the calculation model of the wind deflection angle is revised. Afterward, the deficiency of the wind angle calculation under the static equilibrium method is analyzed; The wind load adjustment coefficient is studied on the problem that the value calculated by the formula is smaller than the actual value. Finally, it also includes the study on wind deviation under pulsating wind.

Introduction

In recent years, high voltage overhead transmission lines continue to occur wind fault flashover failure in our country and the frequency of this has exceeded the acceptable limitation of safe operation. In contrast to lightning flashover and operational flashover, the majority of wind-induced flashover occurs at the operating voltage and cannot be successfully reclosed, which result in the outage of the line and cause significant losses to the national economy.

Tower planning is a very important part of transmission line design. The design of the tower should meet the requirements that insulator string can maintain sufficient electrical clearance on the tower without flashover in the case of the insulator string in the wind under the action of this offset. At home and abroad many scholars have carried out a special analysis and experimental study for the wind partial flashover phenomenon. According to the related literature, the main research contents are as follows: wind pressure asymmetric coefficient; shape coefficient of split conductor; wire suspension method and wind deviation under pulsating wind. Many of the literature analyze this project on the basis of the original calculation method but there are some literatures get some more realistic conclusions through simulation or test. This paper not only aims to summarize some current research results but also puts forward some own views and solutions.

Methodology

Due to the complexity of calculation, the chord polygon method is not widely used in the design, but the straight bar method are broadly utilized because it is simple and clear in calculation [1]. The
rigid straight bar method usually assumes that the suspension insulator string is a uniform rigid straight rod. The loads acting on the straight bar are: the gravity load \( G_v \) and horizontal wind load \( G_k \) at the center of the straight rod; the gravitational load \( W_v \) and horizontal wind load \( W_h \) at the end of the rod as shown in Fig. 1.

![Fig. 1, Force diagram of suspension insulator string](image)

According to the static balance of the rigid rod in the wind-induced deflection state [2], the wind deflection angle of the insulator string can be calculated as

\[
W_h = P_i\left(\frac{l_{10} + l_{20}}{2}\right) + 2T_0\sin\frac{\psi}{2}
\]

(1)

\[
W_v = P_v\left(\frac{l_{10} + l_{20}}{2}\right) + \frac{T_0}{P_i}\left(\frac{h_{10} + h_{20}}{l_{10}}\right) = P_v l_v
\]

(2)

\[
\varphi = \arctan\left(\frac{0.5G_h + W_h}{0.5G_v + W_v}\right)
\]

(3)

In the above formulas, the meanings of the symbols are as described above. Because the influence of the height difference angle has been neglected, the calculation error of \( W_h \) and \( W_v \) is relatively large, which affects the result of wind deflection. According to the simplified formula for the calculation, for the case without height difference, more accurate results can be obtained. As can be seen from the above formula, for the height difference or even larger height difference condition, when the vertical load increases, the wind angle will reduce. The vertical load on the transmission line of the adjacent transmission tower will be very different from the situation of the height difference of zero, so it will cause a prodigious error and exist serious risks. Therefore, when the height difference can’t be neglected, considering the introduction of the height difference correction factor \( \eta \), modifying wind deviation formula can improve the calculation accuracy [3].

\[
W_v = P_v\left(\frac{l_{10} + l_{20}}{2}\right) + \frac{\eta T_0}{P_i}\left(\frac{h_{10} + h_{20}}{l_{10}}\right)
\]

(4)

In order to get the value of \( \eta \), we need to carry on the simulation experiment to a specific line parameter to obtain the massive data and reanalyze them. Although it can improve certain accuracy, but its flaw lies in the universality is not strong and needs the concrete line specific analysis.

**The wind bias model based on the stress variation of the suspension point**

As shown in the Fig. 2 and Fig. 3, A and B are the positions of the lowest point of the string of insulators of adjacent unequal towers. When the wind is stationary, its position is in \( AO' B \), but in the case where the wind speed is blown in the \( AZ \) direction, the wire moves to the \( AOB \) plane position because of the force of wind. At this moment the angle between the wire and the vertical plane is \( \theta \), in other words, the wind deflection angle is \( \theta \). At this point, the magnitude and direction of the wire arc stress are changed. Thus, parameters such as span, specific load, height difference, and stress are located in the \( AOB \). Suspension point wire tension \( F \) can usually be decomposed into three components perpendicular to each other. That is, the wire horizontal tension component \( T_0 \), vertical line conductor horizontal stress \( F_h \) and vertical stress \( F_v \). In other words, the tension of the wire at the
suspension point of the tower should be the sum of the three components. According to the above analysis, the wind deviation calculation model can be modified.

![Wind deflection model of conductor](image)

**Fig. 2, Wind deflection model of conductor**

![Decomposition of the force at point B](image)

**Fig. 3, Decomposition of the force at point B**

Yanling Zhang comparing the modified model with the original model for a line parameter, it is found that the calculated wind deflection angle is slightly larger than the original model, but the difference is small [4]. The conclusion is that the influence of the swinging tension of the transmission line on the wind deflection angle is small, but this factor is indispensable in the increasingly compact high voltage transmission line. The frequency of flashover will reduce quickly if the factor is precise considered.

**Wind bias correction under pulsating wind**

When we carry on calculation and research of the wind deviation of insulator string, the wind is normally treated as a steady state wind; in fact, the wind is a dynamic stochastic process. With the great progress of computer software technology, we can use the numerical analysis technique to research the wind-induced partial response of insulator string under dynamic wind. At present, the orthogonal decomposition method and Monte-Carlo method are the most widely used in numerical simulation. Monte-Carlo method is also called numerical simulation method, its basic idea is using the computer to produce enough number to meet the specified statistical characteristics of the excitation samples, and according to the established mechanical model with numerical methods, the solution is determined. Then the corresponding response statistics are calculated from the corresponding number of response samples. Ignoring the severe non-stationary region recorded in the initial stage, the pulsating wind speed history can be regarded as stationary Gaussian process. The simulation method of stationary Gaussian stochastic process can be divided into harmonic superposition method and linear filtering method. Compared with the harmonic superposition method, the linear filtering method has the advantages of low computational complexity and fast operation speed, but algorithm complexity and low accuracy are its severe shortcomings. So we usually adopt the harmonic superposition method [5].
For one-dimensional, $n$-variable, zero-mean Gaussian stochastic processes \{ $V_1(t)$, $V_2(t)$, ..., $V_n(t)$ \}, each random process satisfies zero-mean value, weakly stationary and obeying the normal distribution, the spectral density function can be written as

$$S(w) = \begin{bmatrix} S_{11}(w) & S_{12}(w) & \ldots & S_{1n}(w) \\ S_{21}(w) & S_{22}(w) & \ldots & S_{2n}(w) \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1}(w) & S_{n2}(w) & \ldots & S_{nn}(w) \end{bmatrix}$$  \hspace{1cm} (5)

After calculating the power spectral density matrix $S(w)$, the Cholesky factorization is performed to obtain the lower triangular matrix

$$H(w) = \begin{bmatrix} H_{11}(w) & 0 & \ldots & 0 \\ H_{21}(w) & H_{22}(w) & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ H_{n1}(w) & H_{n2}(w) & \ldots & H_{nn}(w) \end{bmatrix}$$  \hspace{1cm} (6)

$$H(w)^T = \begin{bmatrix} H_{11}(w) & H_{21}(w) & \ldots & H_{n1}(w) \\ 0 & H_{22}(w) & \ldots & H_{n2}(w) \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & H_{nn}(w) \end{bmatrix}$$  \hspace{1cm} (7)

After $S(w)$ is decomposed into the lower triangular matrix $H(w)$, according to theory of Shinozuka [6], the stochastic process \{ $V_1(t)$, $V_2(t)$, ..., $V_n(t)$ \} can be modeled by the following sequence:

$$v_j(t) = \sum_{m=1}^{j} \sum_{l=1}^{N} |H_{jm}(\omega_l)| \cdot \sqrt{2\Delta \omega} \cdot \cos(\omega_l t + \psi_{jm}(\omega_l) + \theta_m)$$  \hspace{1cm} (8) \hspace{1cm} (j = 1, 2, 3, ..., n)

Among them, the wind spectrum is divided into $N$ same parts in the frequency range; $\Delta \omega = \omega/N$ is the frequency increment; And $|H_{jm}(\omega_l)|$ is a modulo of the above-mentioned lower triangular matrix; $\psi_{jm}(\omega_l)$ is the phase angle between two different points of action; $\theta_m$ is evenly distributed random number between 0 and $2\pi$; $\omega_l = l \cdot \Delta \omega$ is the incremental variable of the frequency domain.

After calculating the power spectral density matrix, as long as giving a reasonable choice of the $N$, $W_m$ and $t$, $\Delta t$, you can utilize the simulation of the random process to obtain good results.

To simulate the random wind field, we need the line parameters are: span, the height difference of suspension points of insulator strings of adjacent towers; The parameters of the simulation are: ground roughness coefficient and roughness length and the number of target points needed for simulation, the horizontal spacing between the target points, the average wind speed, cut-off frequency, sampling time, frequency division number. Finally, using MATLAB programming, you can simulate the pulsating wind speed time.

In order to study the effect of pulsating wind on wind deviation of insulator string, Linhai Xiao set up the insulator string-wire coupling model, using ANSYS software for time-procedure analysis [7]. Finally, the conclusion is that the wind angle under the action of pulsating wind can not be expressed by the mean or maximum value; but according to the statistical principle, the mean and the root variance determine a value with a certain guarantee probability to represent, and its expression can be written as

$$\varphi' = \bar{\varphi} + \mu \sigma$$  \hspace{1cm} (9)

$\varphi'$ is the representative value of wind deflection angle; $\bar{\varphi}$ is the mean value of wind deflection; $\sigma$ is root variance, $\mu$ is the guarantee coefficient. Xiangting Zhang pointed out that the value of $\mu$ is between 2.0 and 2.5, the corresponding probability of assurance for 97.73% -- 99.38%, while the standard value of the guarantee coefficient is 2.2 or so [8]. Then the simulation results of different working conditions are obtained by taking different basic wind speeds. Based on this, the value of the ripple increasing coefficient $\beta$ is proposed. At last, the traditional calculation formula of wind deflection angle is revised.

$$\beta = \psi' / \bar{\varphi}$$  \hspace{1cm} (10)
\[ \varphi = \beta \arctan\left( \frac{0.5G_h + W_h}{0.5G_v + W_v} \right) \]  

(11)

According to the ripple increasing coefficient to correct the calculation of the wind deflection angle, it can reduce the error of considering the insufficient effect of pulsating wind on the wind load in the tower design. However, Linhai Xiao only considers one type of wire, so it should take different wire parameters and conditions for simulation analysis, then values of the ripple increasing coefficient will be proposed under different circumstances.

**Conclusion**

The conclusions of our work are drawn as follows:

- Rigid straight bar method to calculate the wind deflection angle in the case of a small tower height difference is small, if the height difference can not be ignored, then consider the introduction of the difference coefficient to enhance the accuracy of the calculation.

- The wind deflection model based on the change of the stress of the overhanging point can reduce the occurrence of the wind induced flashover in a large extent in the increasing compact line.

- The pulsating wind is simulated by the numerical simulation of the pulsating wind, and then the model of the insulator string and the wire coupling is established to obtain the pulsation amplification factor, which can reduce the error of the pulsating wind on the wind load. However, the universal of the coefficient is not strong, so it need to be based on different types of wire for further study.

**References**


