Analysis of adhesion mechanism of 220kV double-split conductor based on response surface method

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Abstract: In order to analyze the adhesion mechanism of 220kV double-split conductors, this paper proposes 4 adhesion factors, including ice thickness, wind speed, span, and initial spacing. Firstly, the mathematical model of wire adhesion is established; then, the iterative method in MATLAB software is used to solve the mathematical model; finally, response surface method is used to analyze the influence of the interaction among the 4 factors on the wire adhesion. The analysis results show that too small initial spacing is the main factor causing conductor adhesion; under the joint action of initial spacing and span, conductor adhesion is most likely to occur.

1. Introduction
Adhesion of bundled conductors will cause accidents such as phase to phase flashover and wire breakage\cite{1-2}. Zhang Biao put forward four adhesion factors, i.e. height difference, icing thickness, span and splitting distance, and analyzed the influence of each factor on conductor adhesion; Liu Zhengquan put forward four adhesion factors, including temperature, wind speed, splitting distance and span, and summarized the law of conductor adhesion\cite{3-4}.

The advantages of the above two scholars' research: 1) The value of the critical adhesion current is used as the standard to measure the difficulty of wire adhesion; 2) The calculation formula of adhesion factors is converted into an equivalent ratio load formula, and a mathematical model is established. The limitations of the above two scholars' research: 1) Only compared the degree of adhesion of each adhesion factor, did not analyze the influence of various adhesion factors on adhesion; 2) The influence of interaction of various adhesion factors on wire adhesion is not analyzed.

In order to fill the blank of the above research, based on the analysis of variance, the influence of various factors on the wire adhesion is analyzed; based on the response surface analysis method, the influence of the interaction of various adhesion factors on the wire adhesion is analyzed.

2. Establish a mathematical model of wire adhesion
2.1. Four kinds of wire adhesion factors equivalent load
Bundled conductors will adhere under special weather conditions such as strong wind, icing or large span. In this paper, four factors affecting conductor adhesion are proposed, including icing thickness, wind speed, span and initial spacing\cite{5-6}.

The equivalent specific load formula of icing thickness is as follows:

$$\gamma_{ice} = \frac{h(b+D)}{A} \times 10^{-1} \times 0.9 \times g_0 \times \left[ \frac{b(b+D)}{A} \right]$$

The equivalent specific load formula of wind speed is as follows:
The equivalent specific load formula of span is as follows:

\[ d = f_{up} - f_{down} \]  

(3)

The equivalent specific load formula of initial spacing is as follows:

\[ \gamma_d = \frac{2 I_1 I_2}{A d} \times 10^{-7} \]  

(4)

2.2. Mathematical model of wire adhesion

The sag formula of the lowest point of conductor is as follows:

\[ f_M = \frac{\gamma l^2}{8 \sigma_0} \]  

(5)

The change equation of conductor stress state is as follows:

\[ \sigma_m = \frac{E \gamma^2 l^2}{24 \sigma_m^2} = \sigma_n - \frac{E \gamma^2 l^2}{24 \sigma_n^2} - \alpha E(t_m - t_n) \]  

(6)

If the sag difference of bundled conductor is less than the diameter of single conductor, it can be judged as adhesion; The mathematical model of wire adhesion is as follows:

\[
\begin{align*}
\gamma_{up} &= \gamma_g + \gamma_{ic} + \gamma_w + \gamma_d \\
\gamma_{down} &= \gamma_g + \gamma_{ic} + \gamma_w - \gamma_d \\
D &= d_0 - (f_{up} - f_{down})
\end{align*}
\]  

(7)

3. Solving mathematical model of wire adhesion based on MATLAB

3.1. MATLAB iterative principle and process

It is a dynamic balance process of electromagnetic force and self gravity of double bundle conductor to change from normal operation state to adhesion state. The magnitude of electromagnetic attraction increases with the increase of conductor current and the decrease of conductor splitting distance; The increased electromagnetic attraction destroys the original equilibrium state of the conductor, making the upper sub conductor move downward and the sub conductor upward, which further reduces the splitting spacing of the upper and lower conductors until the bundled conductors are adhered.

Firstly, the initial iteration point is set, and the equivalent specific load and horizontal stress are calculated by formula (5) and formula (6); then, the current value of the conductor is increased to calculate the specific load and stress under the new state, and the distance between the two sub conductors is recalculated; finally, the conductor spacing is compared with the diameter of a single conductor. If the spacing between bundled conductors is greater than the diameter of a single conductor, the current value is increased to continue the iteration. If the spacing is less than the diameter of a single conductor, the result is output.

3.2. Calculation of initial iteration points and selection of representative working conditions

The specific load of initial state (excluding the specific load of electromagnetic force) is selected as the initial point of iteration, and the initial point remains unchanged during the iteration process. At the initial moment, the upper and lower conductors have the same specific load, but with the increase of conductor current, the total specific load of upper and lower conductors becomes different, and the iterative process begins.

In order to study the influence of four adhesion factors on wire adhesion, the four adhesion factors are divided into three working conditions, and a group of operating parameters is selected as the initial
state, and the initial iteration point is calculated, and then the critical adhesion current value is calculated according to formula (7), the working conditions of adhesion factors are shown in Table 1:

| working condition | icing thickness (mm) | wind speed (m/s) | Span (m) | initial spacing (mm) |
|-------------------|----------------------|------------------|---------|---------------------|
| 1                 | 0                    | 10               | 100     | 200                 |
| 2                 | 5                    | 20               | 150     | 300                 |
| 3                 | 10                   | 30               | 200     | 400                 |

3.3. Simulation results of adhesion factors under different working conditions

The initial current is set to 1000A, and the current iteration step is set to 10A. Figures 1 ~ 4 show the relationship between conductor current and conductor spacing under three conditions. When the wire spacing is 0, the corresponding current value is the critical adhesion current value.

When the icing thickness is 0mm, 5mm and 10mm, the critical adhesion current values of bundled conductors are 1480A, 1550A and 1630A respectively.

When the wind speed is 10m/s, 20m/s and 30m/s respectively, the critical adhesion current values of bundled conductors are respectively 1310A, 1410A, 1550A.
When the span is 100m, 150m and 200m, the critical adhesion current of bundled conductor is 2080A, 1720A and 1550A respectively.

When the initial spacing is 200mm, 300mm and 400mm, the critical adhesion current values of bundled conductors are 1020A, 1170A and 1550A respectively.

4. Interaction analysis of adhesion factors based on response surface methodology

4.1. Working condition selection and variance analysis of four adhesion factors

In order to study the influence of four adhesion factors on wire adhesion and the influence of interaction on wire adhesion, nine representative working conditions are selected based on the principle of orthogonal test, and the critical adhesion current value corresponding to nine groups of representative working conditions is solved by MATLAB iteration method, and the influence degree of various adhesion factors on wire adhesion is analyzed based on variance analysis method, the variance analysis table of critical adhesion current is as follows.

| working condition | icing thickness (mm) | wind speed (m/s) | Span (m) | initial spacing (mm) | Critical adhesion current (A) |
|-------------------|----------------------|-----------------|----------|----------------------|-----------------------------|
| 1                 | 0                    | 10              | 100      | 200                  | 1020                        |
| 2                 | 0                    | 20              | 150      | 300                  | 1090                        |
| 3                 | 0                    | 30              | 200      | 400                  | 1480                        |
| 4                 | 5                    | 10              | 150      | 400                  | 1400                        |
| 5                 | 5                    | 20              | 200      | 200                  | 1020                        |
| 6                 | 5                    | 30              | 100      | 300                  | 1580                        |
| 7                 | 10                   | 10              | 200      | 300                  | 1150                        |
| 8                 | 10                   | 20              | 100      | 400                  | 2010                        |
| 9                 | 10                   | 30              | 150      | 200                  | 1040                        |
| $\bar{K}_1$       | 1196.6               | 1190.4          | 1536.6   | 1026.6               |                             |
| $\bar{K}_2$       | 1333.3               | 1373.3          | 1176.6   | 1273.3               |                             |
| $\bar{K}_3$       | 1400.2               | 1366.6          | 1216.6   | 1630.2               |                             |
| R                 | 203                  | 183             | 360      | 603                  |                             |

The larger the range, the greater the influence of this factor on the wire adhesion. Therefore, the influence degree of the four factors on conductor adhesion is the initial spacing, span, icing thickness and wind speed.

4.2. Interaction analysis of four adhesion factors

In order to analyze the influence of the interaction of various adhesion factors on the wire adhesion, based on the response surface analysis method, the response surface diagram is drawn by using design expert software according to the data in Table 2, and the interaction of adhesion factors is visualized. In Fig. 5-10, the color change of response surface graph from blue to red indicates the change of critical adhesion current value from small to large; the closer the contour line is to the circle, the less significant the interaction on adhesion is; the closer the contour line is to the ellipse, the more significant the interaction on adhesion is.
From Figure 5 to Figure 6, the contour line of icing thickness and wind speed is circular, and the interaction effect on adhesion is not significant; the contour line of icing thickness and span is close to circular, and the interaction effect on adhesion is more significant.

From Figure 7 to Figure 8, the contour line of icing thickness and initial spacing is close to ellipse, and the interaction effect on adhesion is significant; the contour line of wind speed and span is close to ellipse, and the interaction effect on adhesion is significant.
From Figure 9 to figure 10, the contour line of wind speed and initial spacing is elliptical, and the interaction effect on adhesion is extremely significant; the contour line of span and initial spacing is elliptical, and the interaction has a significant impact on adhesion.

5. Conclusion

1. The influence degree of the four adhesion factors on conductor adhesion is: initial spacing, span, icing thickness, wind speed; it shows that the initial spacing and span are the main factors causing the conductor adhesion, and the smaller the initial spacing and the larger the span, the easier the split conductor will be bonded. In the design of transmission line, it is necessary to increase the initial splitting spacing or install spacer.

2. Although the wind speed has the least influence on the wire adhesion, the interaction between the initial spacing and wind speed has a significant impact on the wire adhesion, which indicates that the influence of wind speed can not be ignored. In the process of line inspection, the vertical arrangement of double bundle conductors with large span and small spacing should be focused on investigation.

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