Research of electric field strength on surface of conductor and its splitting type used in extra high voltage substation

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Abstract. Extra high voltage substation is an important part of the whole project locates in high altitude area, so corona audible noise exists around the operation equipment, mainly concentrated in the bundle conductor in the power station. This research on the split form and surface electric field intensity distribution of bundle conductor has a certain degree of theoretical and practical engineering application value. In this paper, an analysis of the classic formula illuminates the conductor split form, conductor diameter, bundle spacing and other factors how to affect the largest surface electric field intensity of the conductor. On this basis, we take a typical extra high voltage substation conductor as the research object. The three-dimensional model of the actual power station has been established with application of finite element simulation method in accordance with actual structure, and a preliminary calculation of surface electric field intensity also been obtained. According to the results, we analyze the reasons cause the serious corona. Then we design three-split conductor instead of two-split one, and make a comparative analysis between the two different forms. According to the three-split form mentioned above, the conductor diameter and bundle spacing are optimized. The research on the electrical field calculation and split form of bundle conductor provides references for the design of substation, and has practical value for the reduction of corona noise.

1. Introduction
As the hub of EHV power grid, EHV substation plays an extremely important role in the construction of power transmission and transformation project. Due to the complex structure of the upper and lower layers of UHV AC substation, various equipment types and connection modes, the corona and noise problems of UHV AC substation at high altitude are particularly prominent [1,2]. Corona in EHV substation is mainly caused by the surface defects of conductor and substation fittings. After optimizing the design scheme and connection mode of substation fittings and improving the manufacturing process, the corona and noise of substation can be reasonably controlled, and the safety and reliability of substation equipment will be improved to a certain extent [3]. However, for the substation with double bundle flexible conductor connection, the situation that the surface field strength of double bundle conductor is high, corona and noise are prone to occur has not been effectively improved [4]. At present, there are two basic connection modes between equipment in EHV substation: tubular bus connection and double bundled conductor connection. As the soft connection between equipment and equipment, and the connection between equipment and upper and lower tower, double bundled conductor connection is widely used in substation. Generally, the environmental problems caused by conductor corona can be solved by reasonably selecting the cross section of conductor and changing the splitting mode of multi bundle conductor [5].

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In view of the serious corona noise of UHV substation conductor in high altitude area, this paper selects the outlet circuit with high reactance of typical UHV substation as the research object, as shown in Figure 1. Combined with the existing classical formula, the theoretical derivation is carried out, and the relationship between the conductor splitting mode and the electric field intensity of the conductor surface is explored by considering the influence of the conductor splitting mode, the diameter of the sub conductor and the distance between the sub conductors. Considering the influence of equipment and substation fittings, the solid modeling and simulation calculation of the power station are carried out to study the size and distribution of the electric field intensity on the surface of the conductor, optimize the diameter and splitting spacing of the sub conductor, and reasonably select the splitting mode of the conductor. The research on electric field calculation and splitting mode of UHV substation conductor in this paper can provide reference for the selection of UHV substation conductor, and has certain practical value in reducing corona noise of conductor.

2. Theoretical analysis of distribution law of electric field intensity on conductor surface

2.1 Peek formula

In practical engineering, a large number of tests conducted by peek show that the initial corona field strength is related to the conductor size, atmospheric state and conductor surface state. Based on the experimental results, it can be concluded that the initial corona field strength of conductor has the following form[6-8]:

\[ E_c = 30.3m\delta(1 + \frac{0.298}{\sqrt{\delta r}}) \]  \hspace{1cm} (1)
Where \( r \) is the radius of conductor and \( \delta \) is the relative density of air. According to equation (1), it can be seen that the atmospheric state has a great influence on the initial field strength of corona. The altitude of an ultra-high voltage power station is about 2500m. The two bundled conductors used in the station are shown in Fig. 2, and the initial corona field strength is very low. Fig. 3 shows the observation results of corona condition of two bundled conductors by using ultraviolet imager. In peek formula, surface roughness coefficient \( m \) is used to characterize the influence of conductor surface state on corona initial field strength \( E_C \) [9,10], \( m=0.82 \) for overall corona, \( m=0.72 \) for local corona and \( m=1 \) for smooth conductor.

According to peek formula, Figure 4 can be drawn. The abscissa is the diameter \( r \) of the sub conductor, and the ordinate is the initial corona field strength \( E_C \). Therefore, for the EHV substation at an altitude of about 2500m, the initial corona field strength \( E_C \) is about 19.50kV/cm. When the electric field exceeds this value, the conductor will have full corona. Through calculation and statistics, for the UHV substation studied in this paper, \( E_{m}/E_C \) can be controlled by 0.8[11], where \( E_m \) guides the maximum electric field intensity on the surface of the line. In conclusion, the control value of \( E_m \) can be 15.51kV/cm at peak value and 11kV/cm at effective value.
2.2 Mangoldt formula

The classical mangoldt formula is used to analyze the electric field on the conductor surface [12]. In the case of three-phase AC line, $Q_1, Q_2, Q_3$ are the instantaneous charges on the bundled conductor, and the Maxwell potential coefficient is shown in equation (2).

$$
\begin{align*}
P_{11} &= P_{22} = P_{33} = \ln(2H / r_{eq}), r_{eq} = R(Nr / R)^{1/N} \\
P_{12} &= P_{21} = P_{23} = P_{32} = \ln(\sqrt{4H^2 + S^2} / S) = \ln \sqrt{1 + (2H / S)^2} \\
P_{13} &= P_{31} = \ln(\sqrt{4H^2 + 4S^2} / 2S) = \ln \sqrt{1 + (H / S)^2}
\end{align*}
$$

The relationship between voltage and charge is as follows:

$$
\begin{align*}
U_1 &= P_{11}Q_1 / (2\pi e_0) + P_{12}Q_2 / (2\pi e_0) + P_{13}Q_3 / (2\pi e_0) \\
U_2 &= P_{21}Q_1 / (2\pi e_0) + P_{22}Q_2 / (2\pi e_0) + P_{23}Q_3 / (2\pi e_0) \\
U_3 &= P_{31}Q_1 / (2\pi e_0) + P_{32}Q_2 / (2\pi e_0) + P_{33}Q_3 / (2\pi e_0)
\end{align*}
$$

The maximum surface electric field intensity of the conductor is as follows:

$$
E_{0m} = \frac{1 + (N-1)r / R}{Nr \ln \left\{ \frac{2H / r_{eq}}{[1 + (2H / S)^2][1 + (H / S)^2]} \right\}^{1/4}} U
$$

For mesophase:

$$
E_{cm} = \frac{1 + (N-1)r / R}{Nr \ln \left\{ \frac{2H / r_{eq}}{[1 + (2H / S)^2]} \right\}^{1/2}} U
$$

Where: $R$-circumcircle radius of the bundled conductor (cm); $S$-phase spacing of bundled conductor (cm); $H$-height of each phase on the ground (cm); $r$-radius of bundled conductor (cm); $N$-number of bundled conductors per phase; $U$-voltage level (kV). The advantage of mangoldt formula is that it can be used to quantitatively study the influence of various factors on the maximum electric field intensity of conductor surface, such as the number of bundled conductors, the height above the ground, the diameter of bundled conductors, the spacing of bundled conductors and so on, and at the same time consider the interaction of three-phase conductors. In the space rectangular coordinate system, take the wire spacing as the $X$ axis, take the sub wire diameter as the $Y$ axis, and take the maximum surface electric field intensity of the wire $E_{cm}$ as the $Z$ axis to make a three-dimensional graph. At the same time, consider the comprehensive influence of the wire diameter of the split sub wire and the wire spacing on the maximum electric field intensity of the wire surface, as shown in Figure 5, and the parameters used in the calculation of the maximum electric field intensity of the wire surface are shown in Table 1.
Tab.1 Parameters for calculating maximum electric field of conductor surface

| Parameter                                      | Maximum operating voltage of the system/kV | Diameter of sub conductor/mm | Number of bundled conductors |
|-----------------------------------------------|--------------------------------------------|-------------------------------|-------------------------------|
| Numerical value                               | 653.1973                                   | 71                            | 2                             |
| Parameter                                     |                                            |                               |                               |
| Maximum electric field intensity on conductor |                                            |                               |                               |
| Parameter                                     | Three phase conductor arrangement          | Phase spacing of three phase conductor/m | Height of three phase conductor to ground/m |
| Numerical value                               | Horizontal                                 | 11                            | 13                            |

Figure 5 shows that the variation trend of the electric field intensity on the conductor surface is intuitively analyzed within the respective variation range of the diameter and spacing of the bundled conductor, and the red line represents the critical corona electric field intensity. Considering the effect of conductor spacing and sub conductor diameter, the maximum electric field intensity on the surface of middle phase conductor is complex, and the general trend is that it decreases with the increase of sub conductor diameter, that is, the effect of sub conductor diameter is greater than that of conductor spacing.

2.3 Calculation of electric field distribution of sub conductor of bundled conductor
The distribution of electric field on the sub conductor is analyzed, as shown in Figure 6. For the two bundle conductor, the field strength at point a is the smallest and that at point B is the largest on the circumference, and the field strength at other points uniformly transits between the two points according to the chord function distribution. For triple bundled conductors, the field strength at point C is the smallest and that at point D is the largest on the circumference, and the field strength at other points uniformly transits between two points according to the chord function distribution.

Figure 6 Intercept path of the surface E-field strength of the bundled conductor
After simulation, the electric field distribution of two and three bundled conductors under peak voltage is obtained, as shown in Figure 7. Figure 7 (a) shows the spatial electric field distribution of the medium phase conductor. The wire diameter, wire spacing and height above ground of the conductor are the same as those calculated by Mangoldt formula. It can be seen that the maximum electric field appears on the surface of the conductor, and its value is 16.10 kV/cm, which is basically the same as the 16.15 kV/cm calculated according to Mangoldt formula; Fig. 7 (b) shows the spatial electric field distribution of three split medium phase conductor. The maximum value of electric field is 13.60 kV/cm, which is basically the same as 13.31 kV/cm calculated by Mangoldt formula, which proves the effectiveness of finite element modeling and simulation.

For the two bundle conductor, the electric field intensity on the conductor surface is intercepted from point a to point B to point a along the circle, and the Figure 8 (a) is obtained. The maximum field strength of the conductor surface appears at point a, and the minimum field strength appears at point B, the field strength of other points evenly transits between two points according to the chord function distribution. For the three bundle conductor, the electric field intensity on the conductor surface is intercepted from d-point to C-point to D-point along the circle with d-point as the starting point, and the figure 8 (b) is obtained. The maximum field strength of the conductor surface appears at point D, and the minimum field strength appears at point C, the field strength of other points evenly transits between two points according to the chord function distribution.
3. Modeling and simulation analysis of bundled conductor in Substation

3.1 Modeling of bundled conductor in actual substation

The research objects of the traverse include four, which are named as No.1-4 traverse respectively, and the specific number is shown in Figure 9.

According to the symmetry, 1/2 model is established for finite element simulation. In the calculation, the voltage applied to the conductor and voltage sharing fittings is the highest effective value of the operating phase voltage of the system, i.e. 441.673kV. Apply zero potential to the equipment base and earth. The field intensity is intercepted at the maximum field intensity on the circumference of the conductor. The intercepting direction of No. 1 and No. 2 conductors is from right to left, and the intercepting direction of No. 3 and No. 4 conductors is from bottom to top.

3.2 Calculation results of two bundle conductor

The overall potential and electric field distribution of substation calculation model is shown in Figure 10. In order to explain the average level of electric field intensity, the concept of average electric field intensity is introduced. The path along the wire length is the integral of the maximum electric field intensity along the surface, that is, \[ j = \int_0^S E_{\text{max}} dS \], \( S \) is the wire length. On this basis, take the average value, \[ E_{\text{mean}} = \frac{1}{S} \int_0^S E_{\text{max}} dS / S \]. The distribution of electric field strength along the conductor is shown in Fig. 11.
It can be seen from table 2 that the maximum electric field strength of the double split conductor is greater than the control value, and appropriate measures should be taken to reduce the corona effect. According to the in-depth analysis of mangoldt formula, combined with the actual situation of the power station, it is proposed to replace the conductor with three bundle design.

### Tab.2 Calculation results of the surface E-field strength of the two bundled conductor

| Conductor length (mm) | Maximum field strength (kV/cm) | Control value (kV/cm) | Average field strength (kV/cm) |
|-----------------------|-------------------------------|-----------------------|------------------------------|
| 11700                 | 13.16                         | 11                    | 9.342                        |
| 23667                 | 14.40                         | 11                    | 9.338                        |
| 9362                  | 12.67                         | 11                    | 9.732                        |
| 16676                 | 12.12                         | 11                    | 10.14                        |

#### 3.3 Calculation results of three bundle conductor

On the basis of the two bundle model, the conductor is changed into three bundle form, keeping the diameter $r$ of the bundle sub conductor and the bundle spacing $r$ unchanged. According to mangoldt's analysis, the three bundle conductor can effectively reduce the electric field on the bus surface. Compared with the two bundle conductor, as shown in Figure 12, the red line represents the two bundle conductor, and the black line represents the three bundle conductor.
According to the analysis in Fig. 12, for No. 1 and No. 2 conductors, the decrease of field strength mainly occurs between the devices; for No. 3 and No. 4 conductors, the decrease of field strength mainly occurs in the middle area of the conductor. The reason is that near the equipment, due to the shielding effect, the field strength is already very low, and the wires in other places are less affected by the equipment and voltage equalizing fittings. Therefore, by changing the splitting mode, the electric field distribution on the surface of the wire can be improved, and the wire diameter and spacing of the splitting sub wire will be optimized in the future.

4. Optimization of diameter and spacing of bundled conductor

4.1 Diameter optimization of bundled conductor

The actual diameter of bundled conductor in substation is 71mm, and the optimal range of diameter is 51mm to 71mm, in which 5mm is the optimal step. According to the theoretical analysis of mangoldt formula, the maximum electric field intensity on the surface of the conductor decreases with the increase of the diameter of the sub conductor, and there is a saturation effect. For each research conductor, the control value of 11kV / cm corresponds to a certain sub conductor diameter, which can be obtained by fitting function. The fitting function can be described as follows:

$$E_{max} = E_{base} + A_4 e^{-\frac{(d-d_0)^2}{B_1}}$$  (7)

$E_{max}$ is the maximum field strength of the conductor, $E_{base}$ is the basic component of the field strength, and $D$ is the diameter of the sub conductor. The fitting results are shown in Figure 13. It can be seen that with the increase of sub conductor diameter $R$, the maximum
electric field intensity on the conductor surface has a decreasing trend, which is consistent with the conclusion derived from the classical formula. At the same time, there is saturation effect. The specific values of fitting parameters are shown in Table 3.

![Graphs of fitting curves](image)

**Fig. 13** The fitting curve of the exponential function

**Tab. 3 Exponential function fitting result**

| Parameter | Conductor 1# | Conductor 2# | Conductor 3# | Conductor 4# |
|-----------|--------------|--------------|--------------|--------------|
| $E_{\text{base}}$ | 879.8        | 1031.7       | 871          | 964.4        |
| $d_0$     | 51           | 51           | 51           | 51           |
| $A_1$     | 308          | 287.5        | 316.4        | 214.4        |
| $B_1$     | 9.03         | 9.15         | 12.28        | 8.87         |

However, considering the control value of 11kV/mm, it is necessary to select the appropriate sub conductor diameter $r$ from the curve, so that the maximum electric field intensity on the surface of all studied conductors is lower than the control value, and the sub conductor diameter $r$ should be reduced as far as possible. According to equation (7), the diameter of the bundle conductor can be taken as 64mm.

### 4.2 Diameter optimization of bundled conductor

The actual spacing of bundled conductors in substation is 400mm, and the optimization range of conductor spacing is from 100mm to 600mm, with 50mm as the optimization step. Because the maximum electric field intensity on the conductor surface has extremum when the conductor spacing...
changes, polynomial fitting has better approximation effect. Take the order as 3, and the fitting function is described by the following formula:

$$E_{\text{max}} = P_1 R^3 + P_2 R^2 + P_3 R^1 + E_{\text{base}}$$ (8)

It can be seen from Fig. 14 that there are extreme values for each curve of No. 1 ~ No. 4 conductor, which is the best point in design, which is consistent with the previous theoretical demonstration. The conductor spacing should be consistent, and the conductor spacing at the best point should be analyzed among different conductors to determine the final value of the spacing.

![Fig.14 The fitting curve of the polynomial function](image)

| Parameter | Conductor 1# | Conductor 2# | Conductor 3# | Conductor 4# |
|-----------|--------------|--------------|--------------|--------------|
| $P_1$     | 0            | 0            | 0            | 0            |
| $P_2$     | 0.0055373    | 0.0055111    | 0.029542     | 0.0062907    |
| $P_3$     | -2.4813      | -2.5741      | -6.2771      | -2.9089      |
| $E_{\text{base}}$ | 1327.5      | 1483.7       | 1570.4       | 1482.1       |

For design considerations, the conductor spacing should be as small as possible under the condition of ensuring that the surface field strength of the conductor is within the control range, which can save space and make the equipment room more compact. The parameter fitting results are shown in Table 4. The conductor spacing is based on the No. 2 conductor and is taken as 360mm. In this case, the change of the maximum field strength of the other conductors is very small, which basically maintains the field strength value at the optimal conductor spacing.
5. Conclusion

1) With the increase of sub conductor diameter, the maximum electric field intensity on the conductor surface will decrease, and there is saturation effect; with the increase of conductor spacing, the maximum electric field intensity on the conductor surface changes more complex, and there is a minimum.

2) For high altitude EHV substation, two splitting mode is adopted, and the maximum field strength of each conductor exceeds the control value. After the splitting mode is designed as three splitting mode, the maximum field strength of the conductor is significantly reduced, meeting the control requirements. The final optimization result is that the sub wire diameter is 64mm and the wire spacing is 360mm, which can achieve the optimization goal.

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