Calculation and application of surface nominal electric fields of ±1100 kV UHVDC power lines

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Abstract. Electric field strength is one of fundamental electromagnetic environmental parameters for the design of ultra-high voltage direct current (UHVDC) power lines and towers when considering human exposure and transient shock. In order to investigate the impacts of power lines’ geometric parameters on the nominal electric fields on the surfaces of ±1100 kV UHVDC subconductors, charge simulation method is used for calculations. The algorithm is verified by both verification nodes’ potentials in the process and measurement experiments in the laboratory. The geometric parameter of sub-conductor radius has the most obvious effect on the field. When the radius varies by 10%, the electric field strength on the sub-conductor’s surfaces may change approximately by 8%. Calculation results demonstrate that increasing sub-conductor radius may be most effective measure to restrict the electric field on the ground.

1. Introduction
Direct current power transmission with the voltage level equal to or larger than 800 kV is known as the ultra-high voltage direct current (UHVDC) power transmission, which is one of the two significant transmission configurations in the world. In recent decades, tens of ±800 kV and even ±1100 kV UHVDC power projects have been in operation in China [1, 2].

The electric field strength, ionic current density, radio interference (RI), and audio noise (AN) are several electromagnetic environmental parameters for the design of UHVDC power lines and towers. According to the parameter limits [3], the field strength on the ground under the overhead power lines should be less than 30 kV/m considering human exposure and transient shock. The structures of the power lines should be improved or other measures should be used if the field strength is over the limit value.

The electric field or known as the ionized field of UHVDC power lines consists of two portions: the nominal field generated between the high-voltage lines and the ground, and the atmospheric ions’ field generated from corona discharges on the lines. The nominal fields impact the electromagnetic environmental parameters significantly and are of interest for researchers.

Lu [4] gave the calculation results of the nominal electric fields on the surfaces of the ±1100 kV sub-conductors and discussed the influence of the fields on RI and AN. The field results were calculated from charge simulation method (CSM). However, calculation errors or verification experiments were not offered. Zou [5] proposed a new algorithm of upstream boundary element method (BEM) to compute the ionized field of the UHVDC power lines on the ground. The numerical calculation error of the upstream BEM may be less than 0.1% when compared with the analytical solution. But RI, AN, or the field distribution with the presence of human beings was not discussed.
In this paper impacts of power lines’ geometric parameters on the nominal electric fields on the surfaces of ±1100 kV UHVDC sub-conductors are calculated by CSM. These geometric parameters are power line height $H$, pole spacing $L$, sub-conductor distance $D_s$, and sub-conductor radius $R_s$. The calculation method is verified by both calculation results and measurement experiments in the laboratory.

The calculation method of CSM used in this paper is one of standard algorithms in electromagnetics computation. Calculation results of the nominal electric field of ±1100 kV power lines and its influences factors may provide some useful reference for the design and operation of UHVDC because the highest voltage level power transmission project in the world (±1100 kV Changji to Guquan UHVDC Project in China) has been in operation in less than half a year.

2. Algorithm

The schematic view of the tower of bi-polar ±1100 kV ultra-high voltage direct current power lines is demonstrated in figure 1 [4, 5]. The values of sub-conductor number $n$ of each polar, height $H$, pole spacing $L$, sub-conductor distance $D_s$, and sub-conductor radius $R_s$ are 8, 27 m, 28 m, 0.5 m, and 4.74 cm, respectively.

![Figure 1. Schematic view of the ±1100 kV power tower.](image)

Charge simulation method (CSM) is applied in this paper to calculate the electric field strength on the surfaces of the UHVDC power lines. The algorithm is one of the main and standard numerical computational methods of electrostatic field [6]. Firstly, the type of simulation charges in the surfaces of the power lines are determined, which is the infinite line charges; therefore, the configuration of the calculation domain is two-dimension (2-D). Secondly, the potential match points on the high-voltage boundaries are set under the given voltages, namely ±1100 kV. The number of the simulation charges is the same with the one of match points. Lastly, nodal potentials and electric fields in the calculation domain may be obtained by the results of the simulation charges.

The relation between simulation charges and given potentials are written as [7]

$$[P][Q] = \{\phi\}$$

where $\{Q\}$ is the column vector of simulation charges, C/m; $\{\phi\}$ is the given potentials of match points on the power line surfaces, V; $[P]$ is the matrix calculated by the configuration of simulation charges and match points, dimensionless.

The element of matrix $[P]$ is calculated by [4]

$$P_{ij} = \frac{1}{2\pi\epsilon} \ln \left(\frac{(x_i - x_j)^2 + (y_i + y_j)^2}{(x_i - x_j)^2 + (y_i - y_j)^2}\right)$$

(2)
where \((x_i, y_i)\) and \((x_j, y_j)\) are the coordinates of match points and simulation charges, m.

3. Verification

The verification of the algorithm is carried out by two sides. The first is to compare the potentials of the points on UHVDC power line surfaces with the given boundary conditions. The second is to perform measurement experiments of electric field distribution in the laboratory.

There are 25 verification points on each sub-conductor in the algorithm. Calculations results of the average HV sub-conductor’s potential are illustrated in Table 1. The geometric conditions of the power tower are shown in Figure 1. The coordinates of verification points are different from the match points in order to examine the accuracy of the algorithm.

| Polarity | Sub-conductor No. | Average potential (V) | Relative error \((\times 10^{-6})\) |
|----------|-------------------|------------------------|-------------------------------|
| Positive | 1                 | -1099999.951           | 4.47                          |
|          | 2                 | -1099999.950           | 4.51                          |
|          | 3                 | -1099999.951           | 4.47                          |
|          | 4                 | -1099999.948           | 4.69                          |
|          | 5                 | -1099999.948           | 4.69                          |
|          | 6                 | -1099999.950           | 4.51                          |
|          | 7                 | -1099999.950           | 4.55                          |
|          | 8                 | -1099999.951           | 4.47                          |
| Negative | -1                | -1099999.949           | 4.62                          |
|          | 2                 | -1099999.950           | 4.58                          |
|          | 3                 | -1099999.951           | 4.47                          |
|          | 4                 | -1099999.951           | 4.47                          |
|          | 5                 | -1099999.952           | 4.36                          |
|          | 6                 | -1099999.950           | 4.55                          |
|          | 7                 | -1099999.950           | 4.58                          |
|          | 8                 | -1099999.948           | 4.69                          |

As can be seen in Table 1, the calculation results agree with the given boundary conditions. The magnitude order of the relative error between calculations and given conditions is \(10^{-6}\), which verifies the validity of the algorithm and the results.

Measurement experiments of the electric field distribution on the ground under a HV conductor were also performed to test the algorithm. A stainless steel conductor was utilized as the HV power line, which was connected to a HV power supply (Matsusada AU-120) via a HV cable, as can be seen in Figure 2. The HV conductor was supported by two insulated rods. The height and diameter of the conductor were 0.56 m and 4 mm, respectively. There were two stainless steel spheres at the end of the HV conductor to reduce the edge effect distorting the field uniformity.

Five DC rotating electric field meters, or known as the field mills, were used to measure the field distribution on the grounded plate made of aluminum. The third field mill was directly under the HV conductor. The distance between two adjacent field mills was 0.17 m. To avoid corona discharge, the voltage applied to the HV conductor was less than the corona onset value.

Calculation and measurement results of the electric field strength on the grounded plate are shown in Figure 3. The applied voltages were 40 kV and 20 kV. Relative errors between the calculations and measurements were about 5%, which was much larger than the one between verification points’ potential and the given voltage in CSM. Two main reasons may explain the results. On one hand, the domain of the measurement platform is finite, which is different from the calculation condition of the
infinite area; on the other hand, measurement error of the field mills actually exists though calibration experiments have been carried out.

Figure 2. Measurement platform photograph.

Figure 3. Calculation and measurement results.

4. Calculation results and analysis

Under the geometric conditions shown in figure 1, the calculation results of the surface nominal electric fields of ±1100 kV UHVDC power lines are shown in figure 4. Four main factors influence the electric field strength on the sub-conductors, namely height H, pole spacing L, sub-conductor distance Ds, and sub-conductor radius Rs. In the calculation process the range of one factor varies by ±10% with the other three factors unchanged.

Figure 4. Calculation results of the surface nominal electric fields of ±1100 kV lines.
According to figure 4, the electric fields on the surfaces of the sub-conductors are the most obviously impacted by the line radius for the curve slopes in figure 4(d) are the largest. When the sub-conductor radius decreases and increases by 10% respectively, the electric field strength on the 8th sub-conductor’s surface may change by 8.40% and 6.88%. The variation tends of other sub-conductors are similar with the 8th one. The height and sub-conductor distance have little influence on the nominal electric field on the conductors, which can be seen in table 2. Calculation results also demonstrate that increasing sub-conductor radius may be most effective measure to restrict the field on the ground level and human exposure under the UHVDC lines.

Table 2. Variation of the electric field of No. 8 sub-conductor (Unit: %).

| Factor | -10%  | +10% |
|--------|-------|------|
| H      | +0.56 | -0.40 |
| L      | +2.73 | -2.23 |
| D      | -0.40 | +0.61 |
| R      | +8.40 | -6.88 |

Table 3. Regression analysis results of each factor impact on the electric field.

|       | #1          | #2          | #3          | #4          | #5          | #6          | #7          | #8          |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| H     | -2.96       | -2.96       | -3.48       | -4.44       | -5.19       | -5.04       | -4.44       | -3.48       |
| Intercept | 20.51       | 20.15       | 19.86       | 19.87       | 20.14       | 20.44       | 20.7        | 20.72       |
| $R^2$ | 0.993       | 0.993       | 0.992       | 0.997       | 0.994       | 0.994       | 0.992       | 0.992       |
| L     | -0.176      | -0.159      | -0.134      | -0.116      | -0.111      | -0.126      | -0.151      | -0.174      |
| Intercept | 24.67       | 23.81       | 22.67       | 21.92       | 21.87       | 22.62       | 23.75       | 24.67       |
| $R^2$ | 0.997       | 0.998       | 0.997       | 0.998       | 0.997       | 0.998       | 0.996       | 0.996       |
| D     | 1.80        | 1.12        | 0.40        | 0.10        | 0.12        | 0.72        | 1.40        | 1.96        |
| Intercept | 18.82       | 18.80       | 18.72       | 18.68       | 18.68       | 18.72       | 18.80       | 18.80       |
| $R^2$ | 0.983       | 0.966       | 0.781       | 0.457       | 0.132       | 0.921       | 0.972       | 0.984       |
| R     | -6.36       | -6.25       | -6.15       | -6.08       | -6.11       | -6.19       | -6.30       | -6.36       |
| Intercept | 34.89       | 34.24       | 33.56       | 33.16       | 33.29       | 33.82       | 34.49       | 34.93       |
| $R^2$ | 0.997       | 0.997       | 0.996       | 0.996       | 0.997       | 0.996       | 0.996       | 0.997       |

Referring to table 2, electric field strength exhibits nearly linear correlation with different factors. Regression analysis with $R^2$ values in tabular form are also provided, as can be seen in table 3. Most of the electric field results increase with the factor linearly because the $R^2$ results are larger than 0.99.

5. Conclusions

The nominal electric field strength on the sub-conductors of ±1100 kV UHVDC power lines are investigated by charge simulation method in this paper. The conclusions may be obtained as follows:

- The magnitude order of the relative calculation errors of nodal potential on sub-conductors is $10^{-6}$, thus the algorithm is quite accurately.
- Relative errors between measurements and calculations of the field on the ground are about 5% referring to the verification experiments performed in the laboratory.
- Sub-conductor’s diameter or radius is the most obviously factor to impact the field strength on the conductors, and increasing radius may be the best method to reduce the field strength. The electric field strengths on the conductors change by 8% approximately when the radius varies by 10%.
Acknowledgments
The author thanks the State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources very much for the measurement experiment support.

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