Calculation and Analysis of Electromagnetic Environment Indexes and Influence Factors of ±1100 kV UHVDC Transmission Lines

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Abstract. In order to study the influence of electromagnetic environment of ±1100 kV Changji-Guquan the UHVDC lines, the ground total electric field and ion current density of the HVDC line is studied in this paper by using the charge simulation method and Deutsch's hypothesis-based analytical method. And the correctness of the method is verified by the measured results. The EPRI formula and CISPR formula are applied to study the audible noise and radio interference. At last, the influence of UHVDC transmission line parameters on the electromagnetic environment is analyzed, and the influence factors that restrict the construction of the UHVDC transmission lines are also studied. The results show that the minimum height of the pole is limited by the total electric field strength, and the influence of the roughness coefficient should also be taken into account when calculating the minimum height of the wire, while the selection of the diameter of the wire is constrained by both the ground total electric field and the audible noise.

1. Introduction
Compared with the UHV AC transmission system, the UHV DC transmission system has stronger transmission capacity but less loss. Moreover, the AC systems on both sides do not need to be synchronized. In the event of a fault, the UHV DC transmission system has a small loss compared with AC transmission systems. And it is particularly suitable for long-distance point-to-point and high-power transmission [1]. However, due to the difference between the electromagnetic characteristics of HVDC transmission lines and HVAC transmission lines, the electromagnetic impact of HVDC transmission lines has become one of the important factors affecting the construction and development of HVDC transmission lines [2-3].

As the highest voltage level in the world, the Changji-Guquan ±1100 kV UHVDC transmission project has the largest transmission capacity and the farthest transmission distance. In this paper, four indicators for electromagnetic environment evaluation are selected and analyzed, namely, the electric field effect, the ion current density, the audible noise and the radio interference [4-7]. The parameters
of the line who affect the electromagnetic environment indicators are studied, and the relevant factors who restrict the UHV DC transmission are also analyzed. It has practical significance for the design and construction of UHVDC transmission lines.

2. Electromagnetic Environment Parameter Calculation Method

2.1. Calculation Method for Ground Total Electric Field Strength and Ion Current Density

By an analytical method based on the Deutsch hypothesis, the ground total electric field strength and ion current density are calculated. On solving the total electric field strength, the charge simulation method is first applied to calculate the nominal electric field \( E \) when there is no space charge. According to the assumption that the space charge only affects the amplitude of the electric field while leaving its direction unaffected, the total electric field formula is as follows [8]:

\[
E_s = AE
\]  

(1)

The scalar function \( A \) is:

\[
A^2 = A^2 + \frac{2A\rho_e}{\varepsilon_0} \int_{\phi}^{\phi} E^{-2} d\phi
\]  

(2)

Where,

\[
A_e = E_{in} / E_{max}
\]  

(3)

And \( E_{in} \) is the inception electric field intensity; \( E_{max} \) is the maximum electric field on the surface of the conductor.

To get the conductor surface charge density, the average charge density \( \rho_m \) and the charge density \( \rho \) along the power line are required [9]:

\[
\rho_m = \frac{\varepsilon_0(U - U_n)}{\int_{\phi}^{\phi} E d\phi}
\]  

(4)

\[
\frac{1}{\rho^2} = \frac{1}{\rho_m^2} + \frac{2}{\varepsilon_0 A_e} \int_{\phi}^{\phi} E^{-2} d\phi
\]  

(5)

Different surface charge density has different space charge distribution, thus different average charge density. And the chord-cut iteration method is used to obtain \( \rho_e \); the initial value is set as \( \rho_{e1} = f_1 \rho_m \), \( \rho_{e2} = f_2 \rho_m \); \( f_1 \) is 1.5, \( f_2 \) is 3, and the iterative process is as follows:

\[
\rho_{e(i+1)} = \rho_{e(i-1)} + \frac{\rho_{m(i-1)} - \rho_{m(i-2)}}{\rho_{m(i-1)} - \rho_{m(i-2)}} (\rho_{e(i-1)} - \rho_{e(i-2)})
\]  

(6)

2.2. Radio Interference Calculation Method

The empirical formula for radio interference estimation recommended by CISPR can be used to calculate the radio interference \( R_i \) of the DC transmission line more accurately, expressed by equation (7) [9] [10]:

\[
R_i = 38 + 1.6(E_{max}^{-24}) + 461gr + 51gn + 33lg \left( \frac{20}{D} + \frac{A_0}{300} \right)
\]  

(7)
Where, \( r \) is Subconductor radius, cm;
\( N \) is number of conductor splits;
\( A_h \) is Altitude.

### 2.3. Audible Noise Calculation Method

The calculation method of A-level audible noise \( L_{AN} \) is presented by American Electric Power Research Institute (EPRI) and Bonneville Power Bureau (BPA). This paper uses the EPRI calculation formula [10] [11]:

\[
L_{AN} = 56.9 + 124 \log \frac{E_{\text{max}}}{25} + 25 \log \frac{d}{4.45} + \frac{k}{18} \log \frac{2}{10} - 10 \log D - 0.02D
\]

(8)

Where, \( E_{\text{max}} \) is the maximum field strength of the wire surface, kV/m;
\( K \) —— the number of conductor splits;
\( D \) —— Distance from the positive conductor, m;
\( D \) —— diameter of the Subconductor, cm.

### 3. ±1100 kV UHV DC Line Electromagnetic Environment

#### 3.1. Electromagnetic Environment Limit Requirements

Since there is no executable standard for ±1100 kV UHV DC lines, this paper refers to the electromagnetic environment limit of ±800 kV UHVDC transmission line. The ground total electric field strength and ion current density limit values are listed in Table I [12].

According to the electromagnetic environment study of DC transmission lines, the main source of audible noise \( L_{AN} \) and radio interference \( R_j \) is the positive polarity conductor of the line, and the limit value is specified at the 20 m distance from the center line of the DC conductor to the projection line of the positive conductor [10]. At altitudes of 1000 m and below, 50% of the audible noise produced by corona must not exceed 45 dB, while radio interference requires that radio interference of 80% time, 80% confidence, and 0.5 MHz frequency is not more than 58 dB.

#### Table 1. Limit Values of Synthetic Field Strength and Ion Flow Density

| Area                | Synthetic field strength(kV/m) | Ion flow density(nA/m²) |
|---------------------|--------------------------------|-------------------------|
|                     | sunny day | rain | sunny day | rain |
| Residential area    | 25        | 30   | 80        | 100  |
| Non-residential area| 30        | 36   | 100       | 150  |

#### 3.2. Verification of Total Electric Field Algorithm

In order to verify the effectiveness of the total electric field algorithm, the measurement for the ground total electric field is carried out for the ±500 kV Yihua DC line. The calculated and the measured values of the ground total electric field are compared in Fig. 1. It can be easily observed that the calculated values of the total electric field are consistent with the measured ones. Although the measured data outside the transmission line is larger than the calculated one due to the deviation of the actual measuring point, it can still be concluded that our method is valid and is accurate enough to be applied to the actual project calculation.
Figure 1. Comparison of total electric field calculation and experiment

3.3. Electromagnetic Environment of ±1100 kV UHVDC Transmission Line

Changji-Guquan ±1100 kV UHVDC transmission project has the highest voltage level and the largest transmission capacity. The cross-sectional area of the conductor is 1250 mm². The specific parameters are listed in Table II. An 8-split structure line with the split space of 550 mm is selected. The height of the pole wire of Jiquan line is 26 m and the pole space is 26 m. The roughness coefficient of the dry wire in good weather is 0.45. When the conductor is in the case of fouling, the roughness coefficient is 0.3 [13]. The ground total electric field distribution and ion current density distribution in good weather are shown in Fig. 2 and Fig. 3. The nominal field strength is the same as the total electric field strength distribution. However, since the ground electric field strength is affected by the spatial ions, the total electric field strength is twice that of the nominal electric field. The electromagnetic environment parameters of the Jiquan ±1100 kV line, calculated and listed in Table III, are lower than the reference limit.

Table 2. Wire Parameter Table

| Wire type       | Diameter (mm) | DC Resistance (Ω/km) | Split spacing (cm) |
|-----------------|---------------|----------------------|--------------------|
| JL1/G3A-1250/70 | 47.35         | 0.02291              | 55                 |

Table 3. Electromagnetic Environment Parameter Table

| Electromagnetic environment parameters | Calculated value | Reference limit value |
|----------------------------------------|------------------|-----------------------|
| Maximum total electric field strength (kV/m) | 24.00            | 30                    |
| Maximum ion current density (nA/m²)      | 20.01            | 100                   |
| $L_{AN}$(dB)                             | 39.87            | 45                    |
| $R_{A}$(dB)                              | 46.38            | 58                    |
4. Influencing Factors

4.1. Height of Polar Conductors

With pole spacing of 26 m, the electromagnetic environment parameters of Jiquan ±1100 kV with different conductor heights are listed in Table IV. When the height of the conductor is reduced to 22 m, the ground total electric field strength exceeds the reference limit. As can be calculated, the minimum height which satisfies the limit is 22.5 m. The ground total electric field strength is 29.99 kV/m, and the electromagnetic environment parameters are within the reference limit.

According to the calculation results, as the height of the conductor increases, the parameters of each electromagnetic environment decrease. However, each parameter has a different influence on the height of the conductor. Among them, the total electric field strength and ion current density are the most heavily affected, followed by the radio interference, and finally the audible noise. The rise of the conductor can effectively control the field total electric field strength. As the height of the conductor increases, the decreasing trend of the total electric field strength becomes slower. Therefore, too high a conductor height is meaningless to control the ground field strength, and the conductor height should be determined within an effective height interval.
Table 4. Table of Electromagnetic Environment Parameters for Different Height of Pole Conductors

| Polar wire to ground height (m) | Electromagnetic environment parameters |  |
|-------------------------------|--------------------------------------|--|
|                              | Total electric field strength (kV/m) | Ion flow density (nA/m²) | LAN (dB) | RI (dB) |
| 22                            | 31.0                                 | 38.6                      | 40.9     | 49.1    |
| 24                            | 27.2                                 | 27.5                      | 40.4     | 47.2    |
| 26                            | 24.0                                 | 20.0                      | 39.9     | 46.4    |
| 28                            | 21.4                                 | 15.0                      | 39.4     | 45.6    |
| 30                            | 19.2                                 | 11.4                      | 39.0     | 44.8    |

4.2. Sub-conductor Diameter

The electromagnetic environment parameters under different wire schemes are listed in Table V. The four parameters are greatly affected by the diameter of the sub-conductor, and each parameter decreases as the diameter of the sub-conductor increases. When the diameter of the sub-wire is less than 35 mm, the maximum total electric field strength and audible noise exceed the reference limit. Therefore, in order to meet the requirements of the electromagnetic environment of the UHV DC project, the diameter of the sub-conductor should be greater than 35 mm when selecting the conductor. Besides, the selection is restricted by the ground total electric field strength and audible noise.

Table 5. Electromagnetic Environment Parameter Table of Different Sub-conductor Diameter

| Sub-conductor Diameter (m) | Electromagnetic environment parameters |  |
|----------------------------|--------------------------------------|--|
|                            | Total electric field strength (kV/m) | Ion flow density (nA/m²) | LAN (dB) | RI (dB) |
| 30.0                       | 34.3                                 | 48.1                      | 54.8     | 51.3    |
| 35.0                       | 31.4                                 | 39.4                      | 49.6     | 48.9    |
| 40.0                       | 28.5                                 | 31.2                      | 45.2     | 47.5    |
| 47.4                       | 24.0                                 | 20.0                      | 39.9     | 46.4    |
| 50.0                       | 22.3                                 | 16.3                      | 38.2     | 46.2    |

4.3. Pole Spacing

The height of the pole wire is 26 m, and the electromagnetic environment parameters of Jiouan ±1100 kV with different pole spacing are listed in Table VI. According to the above calculation, the minimum height of the conductor is 22.5 m when the pole spacing is 26 m, and the calculated total electric strength is 29.67 kV/m when the pole spacing is 30 m. The inter-electrode distance increases, the total electric strength can be improved. However, the degree of improvement is limited, and the variation in the total electric strength in Table VI is also small. According to the calculation results, as the distance between the poles increases, the electromagnetic environment parameters decrease. Among them, the ion current density changes the most, followed by the radio interference and audible noise. Therefore, the pole spacing is an effective measure to improve ion current density, radio interference, and audible noise.

Table 6. Electromagnetic Environment Parameter Table with Different Polar Distance

| Pole spacing (m) | Electromagnetic environment parameters |  |
|-----------------|--------------------------------------|--|
|                 | Total electric field strength (kV/m) | Ion flow density (nA/m²) | LAN (dB) | RI (dB) |
| 22              | 24.3                                 | 22.0                      | 41.9     | 47.6    |
| 24              | 24.2                                 | 21.0                      | 40.8     | 46.9    |
| 26              | 24.0                                 | 20.0                      | 39.9     | 45.9    |
| 28              | 23.8                                 | 19.1                      | 39.0     | 45.9    |
| 30              | 23.7                                 | 18.1                      | 38.2     | 45.4    |
### 4.4. Roughness Coefficient

The roughness coefficient of the line reflects the surface condition of the conductor, and it is directly related to the intensity of the inception electric field, which directly affects the distribution of the total electric field strength and ion current density on the ground. The electromagnetic environment parameters of Jiquan ±1100 kV line with different roughness coefficients are listed in Table VII. The pole spacing is 26 m and the pole conductor height is 26 m. When the conductor is fouled, the maximum total electric field strength is 36.15 kW/m. When the minimum height of the pole conductor to ground is 30 m, the maximum total electric field strength of the ground is 29.7 kW/m, which is within the reference limits. Therefore, in order to reduce the impact of raising the minimum height of the conductor to the construction and cost of the project, the conductor should be protected from damage during construction and transportation, and the conductor surface should be clean. What’s more, the minimum height of the pole conductor should consider the roughness coefficient influences.

According to the calculation results, as the roughness coefficient decreases, there is no change in radio interference and audible noise, but the total electric field strength and ion current density increase. Due to the influence of rain, pollution and other factors on the roughness coefficient, the total electric field will increase rapidly, so the total electric field under rain will determine the minimum ground height of the UHVDC transmission line.

| Electromagnetic environment parameters | Roughness coefficient |
|---------------------------------------|-----------------------|
|                                       | 0.30  | 0.35  | 0.40  | 0.45  | 0.50  |
| Total electric field strength (kV/m) | 36.2  | 32.5  | 28.5  | 24.0  | 18.7  |
| Ion flow density (nA/m²)              | 54.1  | 42.7  | 31.3  | 20.0  | 9.3   |
| $L_{AN}$ (dB)                         | 39.9  | 39.9  | 39.9  | 39.9  | 39.9  |
| $R_I$ (dB)                            | 46.4  | 46.4  | 46.4  | 46.4  | 46.4  |

### 5. Conclusion

According to the actual conditions of the ±1100 kV Changji-Guquan UHV DC project, the ground total electric field strength and ion current density of Jiquan line are calculated by the charge simulation method and the analytical method based on the Deutsch hypothesis. Combined with EPRI formula and CISPR formula, the audible noise and radio interference of the line are calculated and studied. The following conclusions can be drawn according to the calculation results:

a) The height of the transmission line dominates among the factors which impact on the electromagnetic environment, especially for the total electric field strength and ion current density control. Whereas, it should be noted that the height of the transmission line does not have to be too high, which should be determined in the height range where the total electric field strength is effectively reduced. What’s more, the height of the transmission line should be determined by the size of the total electric field in the rainy day.

b) The degree of improved total electric field strength is limited as the distance between the poles increases. However, the distance between the poles is an effective measure to improve the ion current density, radio interference and audible noise.
c) The electromagnetic environment parameters are bettered with the increase of the diameter of the sub-wire. However, the choice of transmission line diameter is limited by the total electric field strength and audible noise.

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