Analysis of Electromagnetic Environment and Influencing Factors of Yihua DC Transmission Lines

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Abstract. The electromagnetic environment of transmission lines is one of the major constraints to the design and construction of HVDC transmission lines. In this paper, the charge simulation method and the analytic method based on the Deutsch hypothesis are used to calculate the total electric field strength and ion current density of the 500 kV Yihua DC transmission lines, and the correctness of the calculation is verified by the actual measurement results. Then the EPRI formula and CISPR formula are applied to analyse the audible noise and radio interference of HVDC transmission lines. At last, the influence of factors such as the pole spacing of HVDC lines, the conductor height to the ground, the splitting spacing and the roughness coefficient on the electromagnetic environment of HVDC transmission lines are analysed. Among them, the height of conductor has effective impact on the total electric field strength, while the control of polar spacing is limited. The height of the conductor and the distance between the poles affect the level of audible noise and radio interference mostly, but the control effect of the two is opposite.

1. Introduction

Compared with the UHV AC transmission system, the UHV DC transmission system has stronger transmission capacity but less loss, and the AC systems on both sides do not need to be synchronized. Moreover, 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 environment impact of HVDC transmission lines has become one of the important factors affecting the construction and development of HVDC transmission lines [2-3]. The electromagnetic environment impact of DC lines is a major technical issue that must be considered in the design, construction and operation of HVDC transmission lines, including electric field effects, ion current density, audible noise and radio interference [4-7].

As is a common method for calculating the total electric field, the analytic method based on the Deutsch hypothesis is the recommended calculation method for the guide [8], and it is used to calculate
and analyze the ground total electric field of the ±500 kV Yihua line in this paper. The calculation of the nominal electric field and the field strength of the conductor surface are calculated on the basis of the simulated charge method, and the total electric field strength is solved in MATLAB based on the hypothesis of the Deutsch. The effectiveness of the calculation method in this paper is verified by the data in some literatures, and the total electric field intensity measured onsite of ±500 kV Yihua line also verifies the correctness of the method. The research on radio interference and audible noise of Yihua DC line is studied by EPRI formula and CISPR formula [9]. By studying the influence of different line parameters of ±500 kV Yihua line on the three electromagnetic environment parameters, the ground total field strength, audible noise and radio interference, the leading effect of each parameter on electromagnetic environment index is obtained. The work of this paper is of great reference value for line construction and design.

2. Electromagnetic environment parameter calculation

2.1. Conductor surface electric field calculation

The electromagnetic environment parameters of the DC transmission line are closely related to the electric field on the surface of the conductor. The accurate methods for parameter calculation such as Markt-Mendel method, analog charge method, stepwise mirror method, finite element method and moment method, are of great importance [9-10]. The basic principle of the analog charge method is based on the uniqueness of the electrostatic field. The equipotential equations are established using the equivalent substitution method and the superposition principle. After solving them, a set of discrete charge distributions are acquired [11], and the field strength of the observation points can be obtained.

2.2. Audible noise and radio interference calculation method

There are two calculation methods for A-level audible noise in the industry. One is the EPRI method of the American Electric Power Research Institute, and the other is the BPA method of the Bonneville Power Bureau. This paper uses the EPRI calculation formula [9, 12]. For the radio interference estimation, we use the empirical formula recommended by CISPR to obtain the radio interference $R_I$ of the HVDC transmission line [9, 13].

2.3. Ground total electric field strength calculation method and algorithm verification

2.3.1. Ground total electric field strength and ion current density calculation method. According to Deutsch’s hypothesis, the fundamental equation for ground-synthesized field strength $E_S$, space charge $\rho$ and ion current density $J$ are as follows [14]:

$$\nabla E_S = \frac{\rho}{\varepsilon_0}$$

$$J = \rho KE_S$$

$$\nabla \cdot J = 0$$

$$E_S = -\nabla \varphi$$

$$E_S = AE$$

(1)

Where, $\varepsilon_0$ is the dielectric constant of air; $K$ is the ion mobility. When solving the total electric field intensity, first of all, it is necessary to calculate the nominal electric field $E$ when there is no space charge. The nominal electric field $E$ can be calculated by the analog charge method, and then according to the Deutsch hypothesis, the total field strength can be found. The solution formula of $A$ is:
\[ A^2 = A_e^2 + \frac{2A_e \rho_e}{\varepsilon_0} \int_{\phi_1}^{\phi_2} E^{-2} d\phi \]  

(2)

Where,

\[ A_e = \frac{E_{on}}{E_{max}} \]  

(3)

In order to get the surface charge density of the conductor, it is necessary to calculate the average charge density \( \rho_m \) and the charge density \( \rho \) along the power lines separately:

\[ \rho_m = \frac{\varepsilon_0 (U - U_0)}{\int_{\phi_1}^{\phi_2} \int_0^U \frac{d\eta}{E^2} d\phi} \]  

(4)

\[ \frac{1}{\rho^2} = \frac{1}{\rho_e^2} + \frac{2}{\varepsilon_0 A_e \rho_e} \int_{\phi_1}^{\phi_2} E^{-2} d\phi \]  

(5)

\( \rho_e \) is calculated using the secant iteration method, and the initial value is set as \( \rho_{e1} = f_1 \rho_m \), \( \rho_{e2} = f_2 \rho_m \), and \( f_1 = 1.5, f_2 = 3 \). The iterative process is as follows:

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

(6)

2.3.2. Total electric field algorithm verification. In this paper, the difference between positive and negative electrodes is ignored for the calculation of the total electric field and ion current density. In order to verify the correctness and effectiveness of the synthetic electric field algorithm, the maximum electric field and ion current density of the ±800 kV DC transmission line in Jinping-Sunan are calculated by the calculation results proposed in [10]. The results are listed in Table 1 and Table 2. In the table, the calculation results of the total electric field intensity and the ion current density are close to the reference ones in the literature, which proves the validity of the calculation method in this paper.

### Table 1. Maximum total electric field on the ground.

| Polar conductor height (m) | Ground maximum total electric field (kV/m) |
|---------------------------|------------------------------------------|
|                           | Reference value | Calculated value |
| 18                        | 27.0            | 26.0             |
| 21                        | 21.4            | 20.5             |

### Table 2. Maximum ion current density on the ground.

| Polar conductor height (m) | Maximum ion current density on the ground (nA/m²) |
|----------------------------|-----------------------------------------------|
|                            | Reference value | Calculated value |
| 18                         | 34.0            | 33.0             |
| 21                         | 19.0            | 18.1             |

The field strength of the ±500 kV Yihua line was measured using a probe. The measured electric field distribution and the calculated field strength distribution are compared. As can be seen from Fig.
1, the distribution trend of the two curves is almost the same, and the data is basically consistent. The measurement data outside the conductor is larger than the calculated values due to the deviation of the position of the measuring point during the measurement, the method is proved to be effective compared with the literature data and the field measurement data. The process is correct and effective, it can be applied to the actual calculation of the project.

![Figure 1. Comparison of total electric field calculation and experiment.](image)

3. Total electric field strength

3.1. Pole spacing

The variation of the total field strength at different pole spacings is demonstrated in Fig. 2. As the distance increases, the maximum value of the ground total electric field decreases. At the same time, the distribution of the ground synthetic electric field and the position of the maximum value shifts outward. The reason for this is that the density of positive and negative ions between the two poles decreases as the distance between the poles increases, which causes the ground total electric field to decrease. However, when the pole spacing increases from 14 m to 30 m, the maximum value of the ground total electric field only reduces by 3 kV/m, and the magnitude of the decrease is limited. On the contrary, the offset of the maximum position may increase the width of the corridor, which has a negative impact on transmission line planning.

![Figure 2. Total electric field change curve.](image)
3.2. Polar conductor to ground height
The variation of the total electric field strength with different conductor heights is shown in Fig. 3. The lower the conductor, the steeper the electric field distribution trend, and the larger the maximum value of the total electric field. The variation of the maximum value of the ground electric field is demonstrated in Fig. 4. As the conductor height increases, the maximum value of the total electric field decreases rapidly, especially in the line height range of 12 m~20 m, and then the decreasing rate becomes slower. Hence, to meet the requirements of the electromagnetic environment, the height of the polar conductor needs to be controlled. However, the height of the conductor is meaningless for the control of the ground field strength.

![Figure 3. Total electric field change curve.](image1)

![Figure 4. Maximum variation curve of ground total electric field.](image2)

3.3. Split spacing
Considering the line split spacing factor, the total electric field value increases slightly with the increase of splitting spacing, as shown in Fig. 5. The variation curve of the total electric field maximum is demonstrated in Fig. 6. The maximum total electric field strength is only increased by about 1 kV/m before and after, and the variation range is small. It can be seen that both the distribution trend of the ground electric field and the maximum field strength are gentle, so the split spacing is not the leading factor and cannot be used as a control measure for the ground total electric field strength.
3.4. Roughness coefficient

The selection of the line roughness coefficient is directly related to the height of the inception electric field, which in turn affects the strength of the ground total electric field. The selection principle of the roughness coefficient is as follows: the roughness coefficient of the dry conductor in good weather is 0.45, and when the conductor is in the case of fouling, the roughness coefficient is 0.3 [15]. The variation of the ground total electric field under different roughness coefficients is shown in Fig. 7. The distribution trend of the ground total electric field has no obvious change, but the maximum value changes significantly. It can be easily observed from Fig. 8 that the maximum value of the ground total electric field strength decreases as the roughness coefficient increases, and almost linearly changes. The maximum total electric field strength is 21.77 kV/m with the roughness coefficient 0.3, which is about twice the maximum total electric field strength of 12.0 kV/m in good weather. Since the line roughness coefficient is related to the surface roughness of the conductor, the maintenance conductor is not damaged during the construction of the DC transmission line, and the surface of the conductor is kept clean, and the improved conductor roughness coefficient is favorable to the control of the ground synthetic electric field. In addition, due to the influence of the rain, pollution and other factors on the roughness coefficient, the total electric field intensity increases rapidly, so the total electric field in the rainy day is the leading parameter for the design of the minimum height to ground of the DC line.
4. Audible noise and radio interference

4.1. Pole spacing
According to the electromagnetic environment research of DC lines, the main source of audible noise $L_{AN}$ and radio interference $R_I$ is the positive polarity conductor of the line, and the limit value is specified as 20 m outside the project projection of the DC line gear from the center of the positive conductor [8]. The audible noise value and the radio interference value at the outer 20 m of the positive polarity projection are calculated, and the changes under different pole spacings are shown in Fig. 9. It can be easily observed that both $L_{AN}$ and $R_I$ decrease as the distance between the poles increases. However, by comparing the degree of change of the two curves, it is found that the amplitude of the audible noise is larger, and the distance between the poles of the line has a greater influence on the audible noise, so the effect of the pole spacing to control the audible noise is better.

4.2. Polar Conductor to Ground Height
The height of the conductor is increased from 14m to 28m. The variation curve of $L_{AN}$ and $R_I$ is shown in Fig. 10. It can be easily observed that two curves decrease with the height increases, but comparing the changes of the two curves, the variation of radio interference is large, and it can be seen that the effect of the conductor height on controlling radio interference is better.
4.3. Split spacing
In this part, the $L_{AN}$ and $R_I$ of several typical splitting spacing are calculated. The audible noise and radio interference value are the smallest when the splitting spacing is 35 cm. The curve is shown in Fig. 11. The change of the splitting spacing is easy to observe, the changes of the two curves are small. The influence of the splitting spacing being small, hence it is not the main influencing factor of the audible noise and radio interference of the DC transmission line.

Figure 9. Audible noise and radio interference change.

Figure 10. Audible noise and radio interference change.

Figure 11. Audible noise and radio interference change.
5. Conclusion
Based on the Deutsch hypothesis, the ground total electric field of ±500 kV Yihua DC line is studied. The correctness of the calculation method is verified by comparison of literature data and field measurement data. The influence of line parameters on electromagnetic environment is analyzed and the conclusions are drawn as follows.

1) The height of the polar conductor is the leading factor for the strength of the total electric field on the ground and can be an effectively control. At the same time, the minimum height of the polar conductor needs to be determined by the size of the total electric field in the rainy days, and the control effect of the pole spacing on the ground total electric field is weak, thus the width of the line corridor should be increased.

2) Compared with the control effect of the pole spacing and the conductor height on the $L_{AN}$ and $R_i$, the pole spacing can effectively control the audible noise, and the conductor height can effectively control the radio interference.

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