

Influence factors analysis of ionized field characteristics of Zhangbei $\pm 500\text{kV}$ flexible direct current transmission lines

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Abstract. The ionized field should be controlled in order to insure the environmental friendliness of high voltage direct current (HVDC) transmission lines. Different with traditional HVDC transmission lines, the metal return lines is first employed in Zhangbei $\pm 500\text{kV}$ flexible HVDC lines. In this paper, the characteristics of ionized field with and without metal return lines are calculated on the basis of numerical method with Deutsch's assumption. The influence factors, i.e. roughness coefficient, distance between metal return line and height of the metal return line, are analysed in detail. The results show that the metal return lines will have a shield effect on the ionized field on the ground. The distribution of ionized field is nearly independent on the height of metal return line. The shielding effect of the metal return line mainly contributes to the projection position of the metal return line. The presented results can give instructions for the design and control of the ionized field level of flexible HVDC lines with metal return lines.

1 Introduction

In recent years, the voltage source converter (VSC) - based direct current (DC) transmission technology, which can also be called as the flexible direct current transmission technology, has become a hot topic with the large application of the renewable energy in power grid [1]. The first high voltage DC grid in the world, i.e. the $\pm 500\text{ kV}$ flexible direct current grid demonstration project in Zhangbei are constructing in China [2]. This project can play important roles in comprehensive consumption of the renewable energy, i.e. wind and solar power.

In order to insure the economy of the construction of high voltage DC transmission lines, the corona discharge can be permitted as long as the corona discharge is limited at a relatively low level. Along with corona discharge, the space charges can be generated and drifted in the space between the conductor and ground [3-4]. The corona-generated space charges can enhance the electric field and cause the ion current, i.e. ionized field problem. The ionized field may cause the transient electric shock problem and make the people annoyed around the transmission lines if it turns to be higher than the limit value. The ionized field has become one of factors in the design of HVDC transmission line and should be accurately predicted [5].

The ionized field distributions are highly dependent on the corona onset electric field and the structure of the DC transmission line, such as height, polar distance, diameter of the conductors, and et al. Many scholars have investigated the influence factors of ionized field from traditional HVDC transmission lines through theoretical and experimental methods [5-9]. At present,

the prediction methods for the ionized field involve the flux line method [6], upstream finite element method [7], finite difference method [8], and et al. However, different from the traditional HVDC transmission lines, the metal return lines (MRL) are first employed in the 500 kV flexible DC project of Zhangbei [4]. In general, the metal return lines are usually grounded under normal operation conditions. The generation and drift of the space charges may be influenced by the metal return lines [4]. The ionized field characteristics and influence factors under the flexible DC transmission lines with metal return line have seldom been analysed systematically before.

In this paper, the flux line method with the Deutsch' assumption is employed to calculate the ionized field of 500kV flexible DC transmission line in Zhangbei. The influences of the corona onset voltage and structures of polar conductor and metal return line on the distributions of total electric field and ion current density are analysed. Furthermore, the shield effects from the metal return line on the ionized field are also revealed. The presented results can give instructions for the optimal design and environment friendly of the flexible DC transmission lines.

2 Method of analysis

2.1 The governing equations and assumptions

The governing equations in the ionized fields involve the positions equation and the ion current continuity equation which can be given as []

$$\nabla^2 \varphi = -(\rho_+ - \rho_-) / \varepsilon_0 \quad (1)$$

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$$\nabla \cdot \mathbf{J}_+ = -R\rho_+\rho_- / e \quad (2)$$

$$\nabla \cdot \mathbf{J}_- = R\rho_+\rho_- / e \quad (3)$$

where, \mathbf{E}_s is the ionized field, φ is potential in the ionized fields, ρ_+ and ρ_- are positive and negative ion densities respectively, ε_0 is permittivity in air, J_+ and J_- are positive and negative ion current densities respectively, R is ion recombination coefficient in air, and e is charge value of the electron.

The relationships of the ionized field with the potential and ion current density can be expressed as

$$\mathbf{E}_s = -\nabla\varphi \quad (4)$$

$$\mathbf{J}_+ = K_+\rho_+\mathbf{E}_s \quad (5)$$

$$\mathbf{J}_- = K_-\rho_-\mathbf{E}_s \quad (6)$$

where K_+ and K_- are positive and negative ion mobility, respectively.

It is difficult to solve equations (1)-(3) due to the coupling effect of the space charge and the electric field as shown in equations (4)-(6). So the following assumptions, especially the Deutsch's assumption are introduced to simply the above problems.

(1) The space charge only affects the magnitude of the electric field without changing the direction of the electric field, which is called as Deutsch's assumption and can be expressed as

$$\mathbf{E}_s = A \cdot \mathbf{E} \quad (7)$$

where \mathbf{E} is the space-charge-free electrostatic field when the space ions are not taken into consideration and A is a scalar function dependent on position.

(2) The surface field of the conductors remains constant at the onset values after the corona having been stable. This is known as Kaptzov's assumption.

(3) The positive and negative ion mobility is constant.

(4) The thickness of the ionization layer around the conductors is so small as to be neglected with respect to the space between the conductor and ground.

(5) With no consideration of the wind and diffusion of the positive and negative ions is neglected.

(6) There are only positive charges beneath the positive transmission lines and there are only negative charges beneath the negative transmission lines.

Based on above assumptions, the scalar function A can be calculated along the electric field line based on the following equations [6], [9].

$$A\rho = A_e\rho_e \quad (8)$$

$$A^2 = A_e^2 + \frac{2A_e\rho_e}{\varepsilon_0} \int_{\varphi_1}^U \frac{d\varphi}{E^2} \quad (9)$$

$$\frac{1}{\rho^2} = \frac{1}{\rho_e^2} + \frac{2}{\varepsilon_0 A_e \rho_e} \int_{\varphi_1}^U \frac{d\varphi}{E^2} \quad (10)$$

where φ_1 and U are potentials of the start point of the flux line in the integration and applied known voltage on the conductor respectively, A_e and ρ_e are values of A and ion density on the surface of the conductor, respectively.

2.2 The calculation model and boundary conditions

The schematic figure of the structure of the 500 kV flexible DC transmission line with metal return line can be shown in Figure 1. In general, the polar conductors with four-bundles are employed for the 500 kV voltage level transmission lines. While for the metal return line, the two bundles conductors are used. The diameters of the polar conductor and metal return line are 36.23 mm and 26.80 mm, respectively.

The boundary conditions for solving the equations can be given in the following.

1) The potentials on positive or negative polar conductors are 500 kV and -500kV, respectively.

2) The potential on the ground is zero.

3) The metal return lines are grounded under normal operation conditions, and the potential is zero potential.

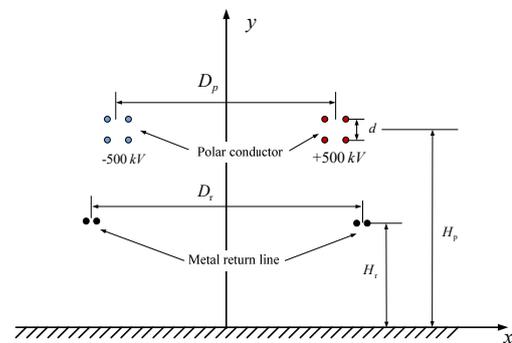
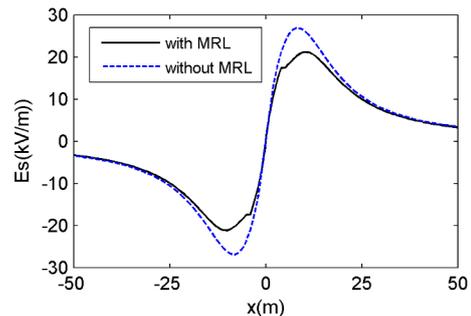


Figure 1. The schematic figure of the 500kV flexible DC line with metal return line

In order to calculate the space-charge-free electric field, the charge simulation method in 2-D is employed [10-11].

3 The distributions of the ionized field on the ground

Firstly, the distributions of total electric field and ion current density with and without metal return line are calculated and shown in Figure 2 (a) and Figure 2(b), respectively. In this case, the polar distance D_p between the positive and negative conductors is set as 12 m, and the distance D_r of metal return line is also 12 m. The heights of the polar conductor and metal return line are 12 m and 6 m, respectively. The corona onset electric field is set as 14 kV/cm.



(a) The distribution of total electric field

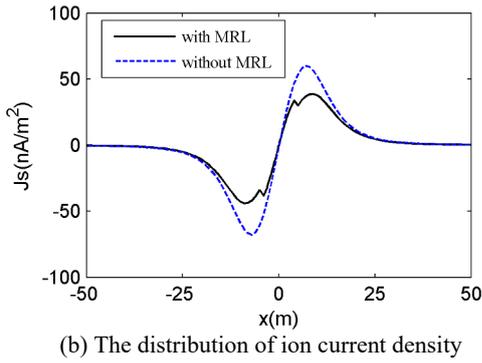


Figure 2. The distribution of total electric field and ion current density with and without MRL

It can be seen from Figure 2 that the appearance of the metal return line can reduce the maximum total electric field and ion current density. Besides, the total electric field and ion current density on the ground around the projection position of the metal return line are also reduced, which may be caused by the shielding effect of the metal return line with ground potential.

In order to show the shielding effect more clearly, the electric field lines in the space are calculated and shown in Figure 3. It should be pointed out that the electric field lines between the positive and negative polar conductors were not given. It can be found that the shielding effect can be clearly identified from the Figure 3.

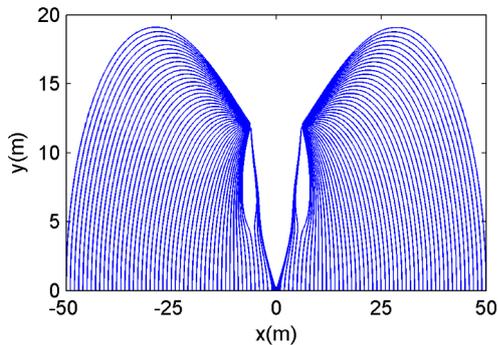


Figure 3. The electric field lines in the space between the conductor and the ground

3.1. The influence of the roughness of the polar conductors

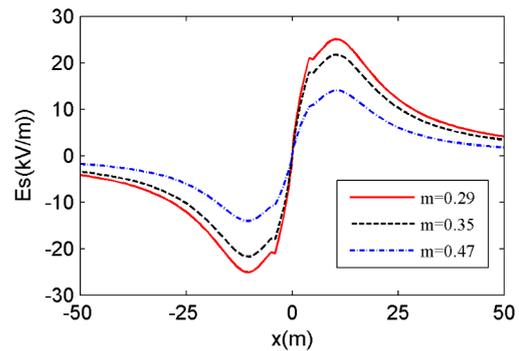
The corona discharge characteristics are highly dependent on the corona onset electric field. For the DC corona discharge, the corona onset electric field for positive and negative corona discharge can be estimated by [6]

$$E_{on+} = 33.7m\delta\left(1 + \frac{0.24}{\sqrt{r\delta}}\right) \quad (11)$$

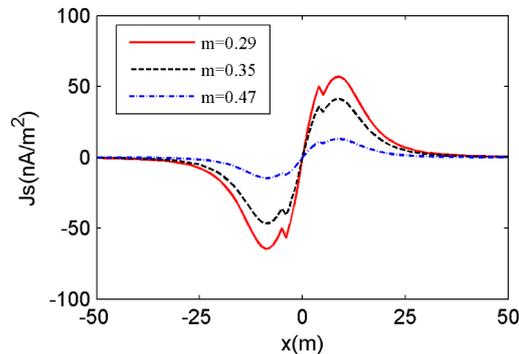
$$E_{on-} = 31m\delta\left(1 + \frac{0.308}{\sqrt{r\delta}}\right) \quad (12)$$

where E_{on+} and E_{on-} are the corona onset electric field for positive and negative corona discharge, respectively, δ is the relative air parameter, m is the roughness coefficient, and r is the radius of the conductor.

In general, the roughness of the conductor is the main factor that affect the corona onset characteristics. The roughness is highly dependent on the weather and the surface state of the conductor. The total electric field and ion current density when the roughness coefficient is equal to 0.29, 0.35 and 0.47, which corresponds to the foul condition, wet condition and dry condition, respectively are calculated and shown in Figure 4. With the decrease of roughness coefficient, the corona onset electric field decreases, and thus the corona discharge degree will be increase at same electric field on the conductor. Therefore, the maximum values of electric field and ion current density increase with the decrease of the roughness coefficient.



(a) The distribution of total electric field



(b) The distribution of ion current density

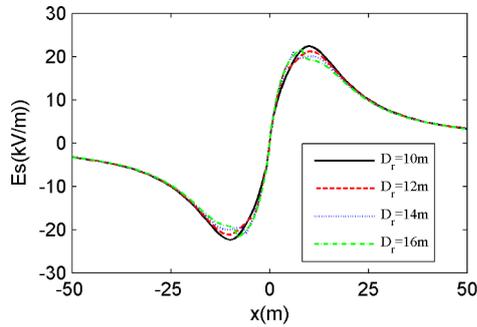
Figure 4. The distribution of total electric field and ion current density at the distances between the metal return lines 10 m, 12 m, 14 m and 16 m

3.2. The influence of the distance between the metal return lines

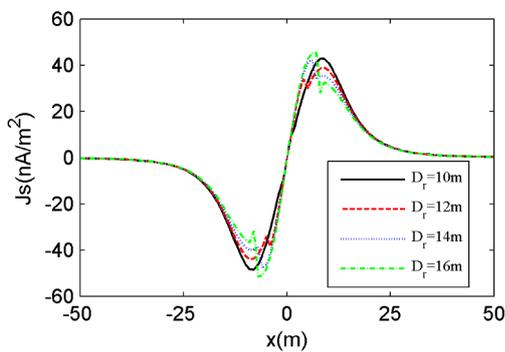
When the parameters of the polar conductors are set as those above, the distances between the metal return lines are set as 10 m, 12 m, 14 m and 16 m to show the influence of the metal return lines. The corresponding calculated results of total electric field and ion current density are given in Figure 5.

It can be seen from the from Figure 5 that the position of the maximum values of total electric field and current density will shift with the position of the metal return line. That means the shielding effect of the metal return line mainly contributes to the projection position of the metal return line. In term of reduction of the ionized field, the position of metal return lines should

be set above the position where maximum total electric field located. Besides, the position of the metal return line should also consider the insulation and construction problems



(a) The distribution of total electric field

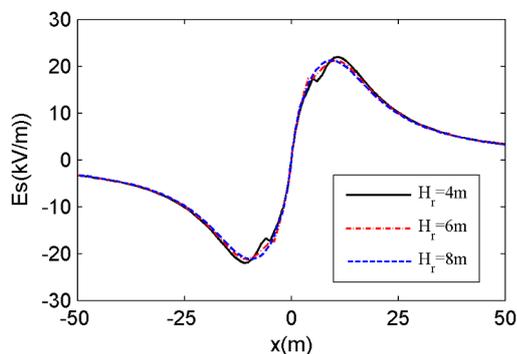


(b) The distribution of ion current density

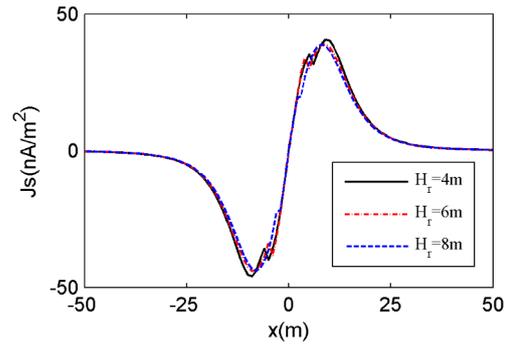
Figure 5. The distribution of total electric field and ion current density at the distances between the metal return lines 10 m, 12 m, 14 m and 16 m

3.3. The influence of the height of the metal return lines

The total electric field and ion current density when the heights of metal return lines are 4 m, 6 m and 8 m are presented in Figure 6 (a) and Figure 6 (b), respectively.



(a) The distribution of total electric field



(b) The distribution of ion current density

Figure 6. The distribution of total electric field and ion current density at different heights of the metal return lines

It can be seen that the ionized field is not sensitive to the height of the metal return lines. The influence of the height of the metal return line on the distribution of ionized can be neglected. The selections of the height of the metal return line should mainly consider the insulation and construction problems in practice.

4 Conclusions

In this paper, the ionized field distributions from the Zhangbei ± 500 kV flexible direct current transmission lines are calculated through the numerical analysis based on Deutsch's assumption. The shielding effect from the metal return line on the ionized field is revealed. Besides, the influence factors, including roughness coefficient of polar conductor, distance between the metal return line and height of the metal return line on the distribution of ionized field are calculated and analysed. The obtained results can give instructions for the design and control of the ionized field of flexible HVDC lines with metal return lines.

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