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Calculation of Surface Electric Fields on the Lighting Conductors near HVDC Transmission Lines

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***Abstract*—Corona discharge may occurs when the lighting conductors are close to the HVDC transmission lines. In this paper, the ion flow electric field on the surface of lighting conductors is calculated by flux tracing method. According to the calculated results, influences of the height, radius and distance of lighting lines on surface electric field are discussed, and the approaches to reduce the electric field strength is given.**

***Keywords*—corona discharge; HVDC transmission; ion flow field; lighting conductor; surface electric field**

I. Introduction

In order to meet the demand of long-distance bulk power transmission, many ultra-high-voltage direct current (HVDC) transmission projects will be operated or constructed in China. Corona discharge occurs when the electric fields around the surface of HVDC lines exceed the corona onset value [1-3]. Electric field, ion current density, space charge density, radio interference (RI), and audible noise (AN) are essential parameters for the design and operation of HVDC lines [4-7].

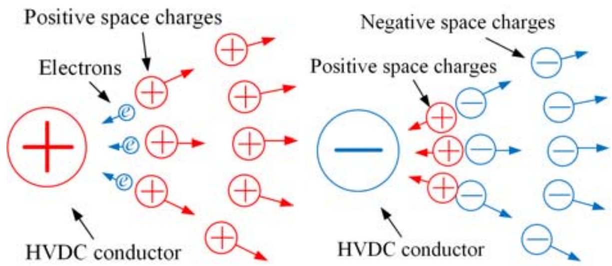
The space charges generated by corona move under the force of DC electric field, and then influence the electric field in the space, which is known as ion flow field problem [8-10]. Because of the effect of space charges, predicting the electric field near HVDC lines is more difficult than that near high-voltage alternating current (HVAC) lines. A variety of ion flow field calculation methods has been proposed [11-13]. The flux tracing method (FTM) is a kind simplified ion flow field calculation method based on the Deutsch assumption [14-17]. This method is recommended in the designing standards of overhead transmission lines, and widely used in the engineering practice [18-22].

Lighting conductors are necessary for protecting the HVDC lines. When the electric fields on the grounded lighting conductors exceed the corona onset value, the corona discharge will happen near the surface of lighting lines [23-27]. Corona of lighting conductors has little influence on the electric field on the ground, but the audible noise and radio interference may be more severe. In the design of lines, the surface electric field on the lighting conductors should be limited. However, the influence of space charges are not considered in the previous surface electric field calculation. In this paper, the ion flow electric field on the surface of lighting conductors is calculated by FTM, and the influence of structures of lighting conductors under different transmission voltages are discussed.

II. Methodology

A. Mathematical Model

In the ion flow field model, the space charges with the same polarity of HVDC conductor drift away from the conductor. Meanwhile, the space charges with opposite polarity move into the conductor, as shown in Figure I(A) and I(B). In Figure 1(B), during the negative corona discharge, the electrons are combined with the air molecule and then form the negative space charges. Expect for the polarity, there is little difference between positive and negative space charges in ion flow field ion flow field. After the corona discharge is stable, the electric field on the HVDC conductor is invariable and equal to the corona onset electric field.



(A) (B)

FIGURE I. SCHEMATIC DIAGRAM OF CORONA DISCHARGE IN ION FLOW FIELD CALCULATION MODEL: (A) POSITIVE POLARITY, (B) NEGATIVE POLARITY.

The electric potential in ion flow field meets the Poisson's equation

$$\nabla^2\varphi = \frac{\rho_+ - \rho_-}{\varepsilon_0} \tag{1}$$

Where φ is the potential in the space, ε_0 is the permittivity in the air, ρ_+ and ρ_+ are the positive and negative space charge density, respectively. The electric field vector $\boldsymbol{E}$ is the negative gradient of the potential function

$$\boldsymbol{E} = -\nabla\varphi \tag{2}$$

The space charges driven by the electric field meet the relationship of current continuity equation

$$\begin{cases} \nabla \cdot \boldsymbol{J}_+ = -R\dfrac{\rho_+\rho_-}{e} \\ \nabla \cdot \boldsymbol{J}_- = R\dfrac{\rho_+\rho_-}{e} \end{cases} \tag{3}$$

$$\begin{cases} \boldsymbol{J}_+ = \rho_+ K_+ \boldsymbol{E} \\ \boldsymbol{J}_- = \rho_- K_- \boldsymbol{E} \end{cases} \tag{4}$$

Where $\boldsymbol{J}_+$ and $\boldsymbol{J}_-$ are the ion current density formed by the movement of positive and negative space charges, respectively. K_+ and K_- are the ion mobility of positive and negative space charges, respectively. R is the ion recombination rate. e is the charge of an electron.

The structure of bipolar HVDC transmission lines with lighting conductors is given in Figure II. D_T, H_T and r_T are the distance, height and radius of transmission lines, respectively. D_L, H_L and r_L are the distance, height and radius of lighting conductors, respectively. d_S is the distance of sub-conductors of transmission lines.

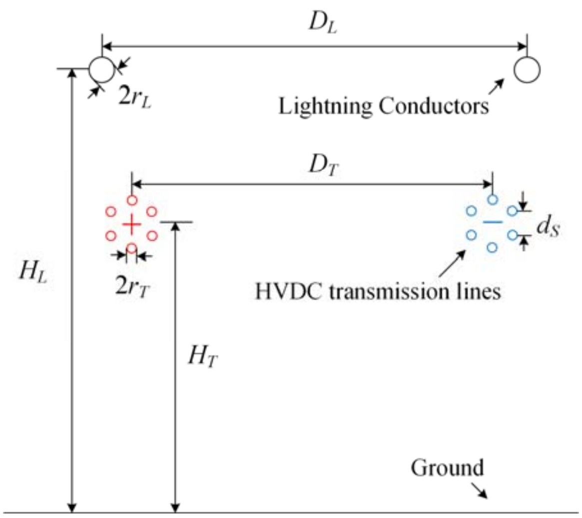


FIGURE II. STRUCTURE OF HVDC TRANSMISSION LINES CONSIDERING THE LIGHTING CONDUCTORS.

B. Calculation of Ion Flow Field

The Deutsch assumption, i.e., the space charges only affect the magnitude of electric field without changing the direction, can be described by the following equations

$$\boldsymbol{E} = \xi \boldsymbol{E}_0 \tag{5}$$

$$\frac{\mathrm{d}\varphi}{\mathrm{d}\varphi_0} = \xi \tag{6}$$

Where $\boldsymbol{E}_0$, φ_0 are the electric field vector and the potential in the space-charge-free electric field, respectively. ξ is a scalar function depended on the position in the space. According to (6), the calculation in 2D space is simplified to the calculation in 1D electric field line, and the Poisson equation (1) can be rewritten as

$$\frac{\mathrm{d}\xi}{\mathrm{d}\varphi_0} = \frac{\rho_+ - \rho_-}{\varepsilon_0 E_0^2} \tag{7}$$

Substituting (1), (2), (4) into (3), the current continuity equation with Deutsch assumption is

$$\begin{cases} \dfrac{\mathrm{d}\rho_+}{\mathrm{d}\varphi_0} = \dfrac{1}{\varepsilon_0 \xi E_0^2}\left(\rho_+{}^2 - \rho_-\rho_+ + \dfrac{\varepsilon_0 R \rho_- \rho_+}{K_+ e}\right) \\ \dfrac{\mathrm{d}\rho_-}{\mathrm{d}\varphi_0} = \dfrac{1}{\varepsilon_0 \xi E_0^2}\left(-\rho_-{}^2 + \rho_-\rho_+ - \dfrac{\varepsilon_0 R \rho_- \rho_+}{K_- e}\right) \end{cases} \tag{8}$$

Consequently, the second-order partial differential equations (1) and (3) are simplified to first-order ordinary differential equations (7) and (8), which are able to solved by finite difference methods.

In (7) and (8), the field strength amplitude E_0 and potential φ_0 in space-charge-free electric field are solved by the charge simulation method. The potential coefficient P_φ with an infinite length line simulation charge is

$$P_\varphi = \frac{1}{2\pi\varepsilon_0}\ln\frac{r_2}{r_1} \tag{9}$$

Where $_1$ and r_2 are the distance from the simulation charge and its image charge to the field point, respectively. The field coefficients P_{Ex} and P_{Ey} are calculated by

$$\begin{cases} P_{Ex} = \dfrac{1}{2\pi\varepsilon_0}\left(\dfrac{x-x_1}{r_1^2} - \dfrac{x-x_2}{r_2^2}\right) \\ P_{Ey} = \dfrac{1}{2\pi\varepsilon_0}\left(\dfrac{y-y_1}{r_1^2} - \dfrac{y-y_2}{r_2^2}\right) \end{cases} \tag{10}$$

Where x, y are the coordinate of field point, x_1, y_1, x_2 y_2 are the coordinate of simulation charge and its image charge. The density of line simulation charge matrix [τ] is

$$[\tau] = [P_M]^{-1}[\varphi_M] \tag{11}$$

Where [φ_M] is the potential matrix of the match points. The match points are located on the conductors, the potential on the match points are known. [P_M] is the corresponding potential coefficient matrix. After obtaining the simulation charge densities, the potential and electric field vector can be calculated by the following equations.

$$[\varphi_0] = [P_\varphi][\tau] \tag{12}$$

$$\begin{cases}[E_x] = [P_{Ex}][\tau] \\ [E_y] = [P_{Ey}][\tau]\end{cases} \tag{13}$$

III. VERIFICATION

A. Validity of Calculation Results

In order to verify the calculation method. The calculated results is compared with the measured ground-level electric fields under an operating ±500 kV transmission lines [28]. Because of the randomness of corona discharge and the outdoor environment, the measured results are unstable to a certain degree. However, the calculated results show the calculation method is able to meet the demand of engineering practice (see Figure III)

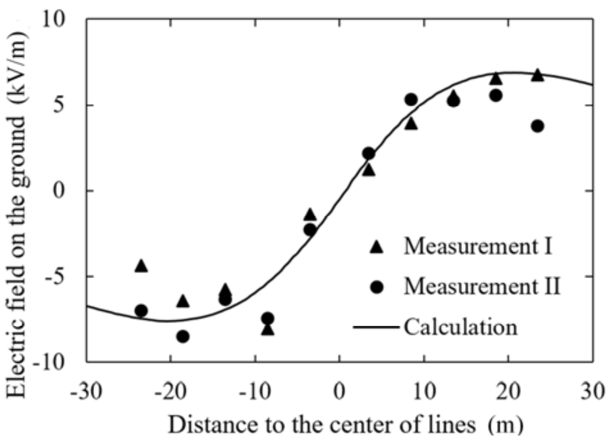


FIGURE III. COMPARISON OF THE MEASURED RESULTS IN [28] AND THE CALCULATED RESULTS IN THIS PAPER.

B. Influence of Space Charges

For the sake of showing the influence tendency of the parameters, the following equation is applied to normalize the calculation results

$$A^* = \frac{A}{A_0} \tag{14}$$

Where A is the actual value of a parameter, subscript "0" represents the reference value, superscript "*" represents the per-unit value. The reference value of electric field on the lighting conductor surfaces is 18kV/m, which is the threshold value of corona discharge in the designing standard. The reference values of transmission lines with different voltage values are listed in Table I.

TABLE I. REFERENCE CALCULATION VALUES OF HVDC LINES

Conductor parameter	**±500 kV**	**±800 kV**	**±1100 kV**
Height of HVDC lines H_{T0}	18 m	22 m	26 m
Polar distance D_{T0}	15 m	18 m	21 m
Radius of sub-conductors r_{T0}	15.1 mm	17.8 mm	19.9 mm
Distance of sub-conductors d_{S0}	40 cm	45 cm	50 cm
Number of sub-conductors N_0	4	6	8
Height of lighting lines H_{L0}	30 m	38 m	46 m
Distance of lighting lines D_{L0}	15 m	18 m	21 m
Radius of lighting lines r_{L0}	7.6 mm	8.3 mm	9.1 mm

Comparison of calculated electric fields on the surface of lighting conductors are listed in Table II. The ion flow electric field is approximate two times larger than the space-charge-free electric field. Therefore, the influence of space charges should be considered in the engineering design.

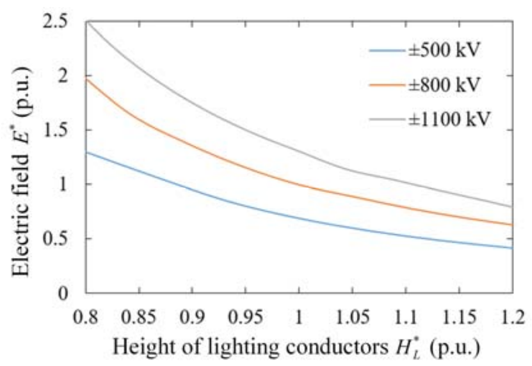
TABLE II. COMPARISON OF THE CALCULATED ELECTRIC FIELDS ON THE LIGHTING CONDUCTORS

Voltage Level	**Space-charge-free Electric Field (kV/cm)**	**Ion Flow Electric Field (kV/cm)**
±500 kV	8.68	12.35
±800 kV	12.02	17.90
±1100 kV	14.56	23.31

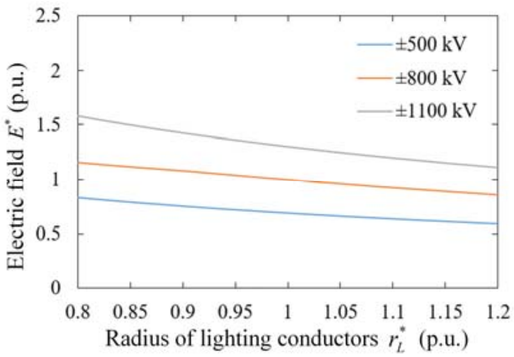
IV. DISCUSSION

In order to reduce the electric field strength on the surface of lighting conductors, the influence of height, radius and distance of lighting conductors are studied. The normalized values are varied from 0.8 p.u. (per-unit) to 1.2 p.u. The calculation results are listed in Figure IV(A), IV(B) and IV(C), respectively.

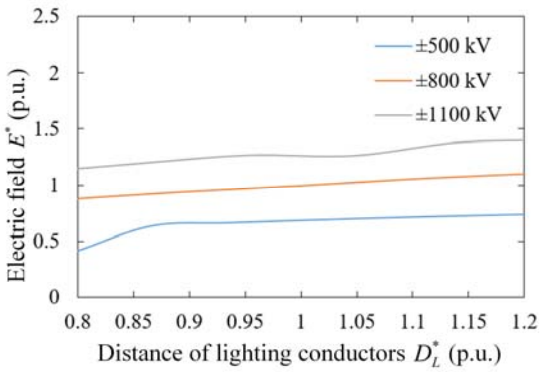
The height of lighting conductors H_L^* is the most important influence factor on electric field. With the increase of the height and radius of lighting conductors, the electric field is reduced. With the increase of the distance from 0.8 p.u. to 1.2 p.u., the electric field is increased. In fact, the electric field will be reduced with further increase of D_L^*, but this situation may not meet the demand of lighting protection.



(A)



(B)



(C)

FIGURE IV. INFLUENCE OF THE PARAMETERS OF LIGHTING CONDUCTORS ON THE SURFACE ELECTRIC FIELDS, (A) HEIGHT, (B) RADIUS, (C) DISTANCE.

V. CONCLUSION

The flux tracing method is applied to calculate the electric field on the lighting conductor surfaces near ±500 kV, ±800 kV and ±1100kV HVDC transmission lines. The calculation method is verified by the measured results under ±500 kV lines. The surface electric fields on the lighting conductor surfaces are significantly influenced by the space charges that generated by corona discharge. The surface electric fields can be reduced by increasing the height and radius of lighting conductors.

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