Calculation Of Ion Flow Field In HVDC Transmission Lines Under The Influence Of Haze

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Abstract. Because of the influence of haze on the electromagnetic environment of HVDC transmission lines, this paper proposes a method for calculating the ion flow field considering the influence of haze based on the flux line method, and takes the Yunguang 800kV UHVDC transmission line as an example. A synthetic field intensity and ion flow calculation model with different haze and haze levels was established, and the resultant field strength and ion flux density under different haze conditions were obtained. The results showed that the ground synthetic field intensity and ion flux density under haze weather increased relative to normal weather, and increased with the increasing degree of haze weather pollution. This calculation method has reference value for the analysis of haze weather and corona impact factors in the planning and design of HVDC transmission lines.

1. Introduction
HVDC transmission has been widely used in power transmission projects in China, and its corona loss, radio interference, ground synthesis field and ion flow density and other factors need to be considered and controlled in the construction. A large amount of research has also been done on this aspect in China. Achieved fruitful results, however, due to the frequent occurrence of hazy weather in recent years, the new complex weather conditions have brought new challenges to the HVDC transmission project. Under hazy weather, there are a large number of suspended droplets and suspended particulates in the air. The space around the transmission line is filled with charged ions. Suspended particles in the smog will absorb charged ions and form new charged particles, which cannot be ignored because of the large number of particles. This makes the calculation of the ion flow field more complicated.

In the calculation of ion flow field, the finite element method or flux line method is usually used, and the finite element method can achieve the calculation of unipolar and bipolar DC ion flow fields, but the calculation efficiency is not high, especially in the model grid. In the complex case, the calculation speed is slow. The flux line method is based on the Deutsch hypothesis. The equation is simple and fast. No mesh is needed. The calculation result is close to the actual measurement result, and it meets certain accuracy requirements. The flux line method is used to calculate the combined field strength and ion flow to meet the engineering requirements.
2. Theoretical Basis

2.1. The Mechanism of Haze on the Electric Field

(1) Influence of haze on space charge density

The influence of haze on the electromagnetic environment is mainly reflected by the effect of suspended droplets and mixed particles of hafnium particles on the flow field of the corona ion. After the transmission line becomes hazy, the suspended droplets and haze particles in the air will be charged. Usually, ions are charged. By means of diffusion charging and electric field charging, it is attached to the droplets and helium particles. According to research, when the particle size of the particles is greater than 0.5, the electric field charging plays a major role, since the particle sizes of the droplets and helium particles are larger than this value, the diffusion charge can be ignored, this article only considers the electric field charge. When the charged electric field generated by the adsorbed ions of the particles is balanced with the external electric field, the charge is saturated and the saturated charge of the particles is:

\[ q_s = \frac{2 \pi \varepsilon_0 E_s r_0^2 \varepsilon_r}{f(\varepsilon_r + 2)} \]

In the formula, \( r_0 \) is the particle radius, \( \varepsilon_r \) is the relative permittivity of the particle.

(2) Effect of haze on ion mobility

A large amount of haze particles and suspended droplets in the air will affect the mobility of ions, which can be obtained according to the calculation formula of ion mobility:

\[ \frac{K_h}{K} = \sqrt{\frac{M}{M_h}} = \sqrt{\frac{m_a + m_h + m_r}{m_a + m_h + m_r}} \]

Among them, the ion mobility under haze conditions is the ion mobility under normal conditions, the relative mass of air molecules under hazy conditions, the relative mass of air molecules under normal conditions, and the air density under normal temperature and pressure. For the density of mist droplets in the air, the moisture content of air at 100% relative humidity is the density of particles in the air, and when severely polluted, the selected concentration is 310. Substitute the values of the parameters into the above equation given:

\[ K_h = 0.991K \]

(3) Effect of haze on the halo field strength of conductor surface

Long-term fogging will increase the degree of contamination of the wire, affect the roughness of the wire, and thus affect the starting voltage of the wire. The humidity in the air under haze conditions is an important factor that affects the field strength of the wire. This has been studied in the literature and the calculation formula has been proposed. The haze field strength under hazy weather can be expressed as:

\[ E_{on}' = \frac{m'}{m} E_{on} \]

\( E_{on}' \) is the haze field intensity under the haze, \( E_{on} \) is the haze field strength under normal weather, \( m' \) is the coefficient of the wire roughness under the haze, generally taken as 0.42, \( m \) is the roughness coefficient under normal weather, generally taken as 0.47.

2.2 Synthetic field strength calculation theoretical basis

2.2.1 Calculation of Synthetic Field Intensity Without Considering Haze

Under normal weather conditions, the spatially synthesized electric field \( E_s \), the ion current density \( J \), and the space charge density \( \rho \), the control equation is:

\[ \nabla \cdot E_s = \rho / \varepsilon_0 \]

\[ J = k \rho E_s \]
\[ \nabla \cdot \mathbf{J} = 0 \]  
(7)

\( k \) is the ion mobility and the space-charged synthesis field equation is non-linear. To facilitate the solution, the following assumptions are often made:

1. The space charge only affects the magnitude of the field strength without affecting its direction, and the Deutsch hypothesis: \( E_s = AE \)  
(8) \( A \) is a scalar function.

2. After the corona, the surface field strength of the conductor is maintained at the halo field strength value. When the voltage of the conductor to the ground is \( U \) and the corrugation voltage of the conductor is \( U_0 \), the \( A \) value of the surface of the conductor is: \( A = U_0/U \)  
(9)

3. Ion mobility is independent of field strength and is constant.

4. The thickness of the corona layer is negligible.

5. Ion diffusion is not considered.

Based on Peek's formula, the formulas for calculating the field strength of the positive and negative wires for DC transmission lines are presented in the literature:

\[ E_{on}^+ = 33.7m\delta(1 + 0.24/\sqrt{\delta}) \]  
(10)

\[ E_{on}^- = 31m\delta(1 + 0.308/\sqrt{\delta}) \]  
(11)

In the formula, \( E_{on} \) is the corrugation field strength of the wire surface, \( m \) is the roughness coefficient of the surface condition of the reaction wire, according to the power industry standard DL/T "High-voltage direct current overhead transmission line technical guide" in the calculation of corona loss, \( m \) is taken 0.47. \( r \) is the sub-conductor radius (cm); \( \delta \) is the relative density of the air. In order to simplify the calculation, the HVDC transmission lines are often replaced by equivalent conductors. The inspiratory field strength of equivalent conductors can be calculated using the formula. According to the previous calculation and comparison of actual measurements, \( E_{on} \) which is the average value of the maximum surface field strength of each sub-conductor is taken in this paper. It can be seen according to the formula (9) that the value of the pole wire surface \( A_i \) is:

\[ A_i = \left| E_{on}/E_{max} \right| \]  
(12)

2.2.2 Calculation of Synthetic Field Intensity Considering Haze

Charged haze particles increase the space charge. The calculation equation for the ion flow field of the HVDC transmission line considering smog particles is listed as follows:

\[ \nabla \cdot \mathbf{E}' = -(\rho_r + \rho_f + \rho_p)/\varepsilon_0 \]  
(13)

\[ \nabla \cdot \mathbf{J}' = 0 \]  
(14)

\[ \mathbf{J}' = K_s\rho_r \mathbf{E}_s + \rho_f \mathbf{v}_f + \rho_p \mathbf{v}_p \]  
(15)

In the formula, \( \mathbf{E}_s \) is the synthetic electric field strength of considering the haze, \( \rho_r \) is the ion space charge density, \( \rho_f \) is the charge density of the suspended droplets, \( \rho_p \) is the space charge density of the suspended germanium particles, \( K_s \) is the ion mobility in hazy weather, \( \mathbf{v}_f \) is the moving speed of the suspended droplets, \( \mathbf{v}_p \) is the moving speed of the suspended particles, \( \mathbf{J}' \) is the ion flux density.

3. Calculation Methods and Steps

Comparing the above control equations, it can be seen that the space charge resulting from the electrostatic charging of the suspended droplets and the helium particles under haze conditions leads to a change in the resultant field strength. Therefore, in the calculation process, the flux line method is first used to determine the inconsistency. The space charge density at the time of haze, plus the charge of the suspended droplets and the niobium particles, is the total space charge density, from which the
resultant field strength considering smog can be calculated. Then, the ion flux density under the haze conditions is calculated by equation (15).

### 3.1 Calculation of Space Charge Density under Normal Weather Conditions

There are many ways to calculate the nominal field strength. This paper uses the optimized simulation charge method. According to formula (8), after obtaining $E$, as long as $A$ is obtained, then $sE$ can be obtained. As long as $\rho$ is obtained, then $J$ can be obtained. According to the formula of calculating the synthesis field with flux line method, we know that:

$$A^2 = A_i^2 + \frac{2A_i\rho_i}{\varepsilon_0} \int_\phi^U E^{-2}d\phi$$

(16)

$$\frac{1}{\rho^2} = \frac{1}{\rho_i^2} + \frac{2}{A_i\rho_i} \int_\phi^U E^{-2}d\phi$$

(17)

In the formula, $A_i$ is the value of $A$ on the surface of the polar wire, $\rho_i$ is the charge density on the surface of the polar wire. For any given $\rho_i$, the average charge density on the power line through any point of space is:

$$\rho_m = \iint_{\Omega} E^{-2} \rho d\eta d\phi$$

(18)

According to the formula derivation, we also know:

$$\rho_m = \varepsilon_0 (U - U_0) \iint_{\Omega} E^{-2} d\eta d\phi$$

(19)

Therefore, after assuming the initial value of $\rho_i$, $\rho_m$ can be calculated by using two formulas separately, if the two answers are equal, the given value is the real value.

According to the flux line method to calculate the synthetic field strength, the following steps are needed:

1. For any point of space as $P(x, y)$, first apply the optimized simulation charge method to calculate the electric field line passing through the point to determine its relative position. If it is located between the positive lead and the earth, then take the parameters of the positive lead to calculate, otherwise, take negative wire parameters.

2. Using equations (12) and (9) to calculate the value of $A_i$ and $U_i$, respectively, substituting (19) to calculate the value of $\rho_m$.

3. Select two initial values of $\rho_i$ on the surface of the wire and use the following formula to make it possible to reach the convergence accuracy of the class as quickly as possible during the subsequent iteration.

$$\rho_{i1} = f_1 \rho_m$$

(20)

$$\rho_{i2} = f_2 \rho_m$$

(21)

In order to make the calculation reach the convergence accuracy of the stage as quickly as possible during the subsequent iteration, according to experience, if it is a positive pole, $f_1$ take 2 and $f_2$ take 3; if it is a negative pole, $f_1$ take 1.5 and $f_2$ take 3.

4. Calculate the charge density values $\rho_1$ and $\rho_2$ corresponding to $\rho_{i1}$ and $\rho_{i2}$ according to equation (17), and then substitute them to equation (18) to find the corresponding solution of $\rho_{m1}$ and $\rho_{m2}$. Then, the further initial values of $\rho_i$ are calculated as follows.

$$\rho_{i3} = \rho_{i2} + (\rho_{i1} - \rho_{i2})(\rho_{m2} - \rho_{m1})/ (\rho_{m2} - \rho_{m1})$$

(22)

5. Same as above, substituting $\rho_{i3}$ into the formula (17), finding the charge density $\rho_i$, and substituting $\rho_i$ into (18), we get the average charge density $\rho_{m3}$ corresponding to $\rho_i$, whether $\rho_i$ is
true value of \( \rho_i \), it can be judged by the following formula:

\[
\left| \frac{\rho_e - \rho_{ei}}{\rho_e} \right| < 10^{-6}
\]

If the above equation holds, we consider \( \rho_0 \) is the true value of \( \rho_i \), otherwise let \( \rho_i = \rho_0 \), \( \rho_i = \rho_3 \), and repeat (4)(5) until the above equation holds.

(6) After obtaining the actual value of \( \rho_i \), the value of \( A \) can be calculated according to equation (16), then substituted it into equation (8), we can obtain \( E \) which is the synthesized field strength without considering the haze.

### 3.2 Calculation of Synthetic Field Intensity Considering Haze

The haze is the collective name for the suspended droplets and particles. The composition of the particles is complex, in this paper, only the effect of PM2.5 on the ion flow is studied. The particle size of suspended droplets is generally greater than 1 \( \mu m \), this article takes 3.2 um, the average diameter of suspended particles is 1 um to 2 um, this article takes 1.3 um. When the synthetic field strength regardless of the haze is calculated out, we can substitute it into the formula (1) to get the saturated charge of suspended droplets and particles. Assuming that the density of suspended particles is \( 1 \text{ g/cm}^3 \), the number of particles per unit volume \( (N_i) \) can be calculated out. The number of droplets per unit volume \( (N_i) \) according to the pollution level were taken from 50 to 300 drops per cubic centimeter, as shown in the following table. As a result, the total charge density taking into haze effects is obtained.

\[
\rho = \rho_e + \rho_f + \rho_p = \rho_e + (N_f + N_p) \cdot q_i \tag{24}
\]

According to the classification of the haze level in China, this paper calculates the unit volume of droplets and haze particles in the corresponding grades, as shown in the following table. The calculation model in this paper assumes that each level of fog is accompanied by a certain amount of fog, i.e., the sum of the corresponding droplets and helium particles in the table below is the total number of charged particles.

| Pollution level | Mass concentration index \((\mu g \cdot m^{-3})\) | PM2.5 mass concentration average \((\mu g \cdot m^{-3})\) | Particle number density \((cm^{-3})\) | Unit volume of droplets \((cm^{-3})\) |
|----------------|---------------------------------|---------------------------------|----------------------------|-------------------|
| Level 3        | 101 ~ 150                       | 120                             | 104                       | 50                |
| Level 4        | 151 ~ 200                       | 180                             | 156                       | 100               |
| Level 5        | 201 ~ 300                       | 250                             | 217                       | 200               |
| Level 6        | >300                            | 310                             | 269                       | 300               |

The resultant electric field at this time is composed of three parts, the nominal electric field generated by the electric charge of the wire, the electric field generated by the charged droplets and helium particles, and the electric field generated by the space corona ion. After calculating out the value of \( \rho_i \) which is the total charge density in consideration of the haze, the value of \( \rho_f \) which is the charge density on the surface of the wire is changed due to the increase in the charge amount of the haze, the value of \( A \) and \( A_i \) are also changed for this reason, so it is necessary to calculate these parameters again. According to formula (17), under the condition that the value of \( \rho_i \) is known, \( \rho_i \) can be derived as follow:

\[
\frac{1}{\rho_i} = \frac{1}{\epsilon_0 A_i} \int E^2 d\phi + \frac{1}{\rho_e} \left[ \int \phi_i (E^2 d\phi) \cdot A_e^2 \right]
\]

(25)

\[
\frac{1}{\rho_i} = \frac{1}{\epsilon_i A_i} \int E^2 d\phi - \frac{1}{\rho_e} \left[ \int \phi_i (E^2 d\phi) \cdot A_e^2 \right]
\]

(26)
If the desired point is located in the area of the positive polarity wire, $\rho^+$ need to be calculated out according to the formula (25), otherwise, it is calculated out according to the formula (26). After obtaining the value of $\rho^+$, we can substitute it into the equation (16) to obtain the value of $A$ which is considered the haze conditions. Then we substitute $A$ into the equations (8) and (15), the synthesized field strength and the ion current density can be obtained.

3.3 Calculation Steps
The general calculation steps are as follows:
1. Calculate the nominal electric field strength using the optimized simulation charge method
2. Calculate the resultant field strength and charge density of the transmission line without considering haze by using the flux line method
3. Calculate the charge of suspended droplets and helium particles to obtain the total charge density;
4. Calculate the surface charge density and $A$ value of the wire considering the haze conditions;
5. Calculate the total combined field strength and ion flux density from the flux line.

4. Calculation Results
Using an 800kV HVDC transmission line as a model, the composite field strength and ion flux density under different haze conditions are calculated. The line parameters are as follows. The wire type is 6 LGJ-630/45, and the sub-conductor radius is 1.68 cm. The distance is 22m, the height of the wire to the ground is 21m, the splitting distance is 0.45m, the corona wire voltage of the anode wire is taken as 604kV, and the corona wire voltage of the cathode wire is taken as -582kV, which is calculated under several different haze conditions. Synthetic field strength and ion flux density are shown in the figure below:

![Fig. 1 Distribution of ground-plane electric field under different fog-haze conditions](image-url)
5. Conclusion

The calculation results show that the ground synthetic field intensity and ion flux density under haze weather increase relative to normal weather, and increase with the degree of pollution of haze weather. In the sixth level of heavy pollution with heavy fog, when the haze concentration is 310 and the number of droplets is 300 drops, the maximum synthetic field strength is 28 kV/m, which is 19% higher than normal weather, and it is close to China. The ground synthetic field strength control standard is 30 kV/m. As the haze increases, it may exceed the control standard. The ion current reaches 37.5nA/m² under the haze conditions, which is 44% higher than normal weather. Therefore, when designing and constructing transmission lines, the characteristics of composite field strength distribution under haze conditions should be considered.

Acknowledgment

Project supported by Fundamental Research Funds for Central Universities of North China Electric Power University (2752015 MS87).

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