Research on Simulation Method of UHVDC Corona Discharge

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Abstract. Ultra high voltage direct current (UHVDC) transmission has taken a significant part in power grid. However, the increase of transmission efficiency hindered by electromagnetic environment problems caused by its corona discharge. Therefore, the corona discharge of UHVDC transmission line has been spotlighted. Considering the complex reaction of microscopic particles in the air during the discharge process, this paper integrates each split conductor as a discharge source located on the split centerline, and simplifies the discharge of the transmission line into a one-dimensional model of a coaxial cable. The study can help us to explore the physical process and microscopic particle motion characteristics of corona discharge deeply. Besides, it is an important guideline for studying and preventing electromagnetic environment problems from the root cause.

1. Introduction

Ultra high voltage direct current (UHVDC) transmission has lately received great use for international power grids own to its low line losses. Nonetheless the electromagnetic environment problem due to corona discharge cause a lot of interference to the lives of residents around the line. To study corona discharge by numerical simulation, the effect of temperature, humidity, wire properties as well as other factors on corona discharge can be studied by changing the parameters in simulation model, which provides a theoretical basis for the indirect detection of corona effect.

Numerical simulation method is a method which simulates the change of electric field and charged particle motion during corona discharge by hydrodynamic theory and electromagnetic field equation, and then calculates the value of corona current by space charge distribution. With the help of computer, numerical simulation method can be used to study the effect of various factors on corona discharge by adjusting parameters, and acted a critical role in the study of corona discharge.

The common numerical simulation models for corona discharge are mainly hydrodynamic models and plasma models. Morrow et al. proposed the most famous one-dimensional model of Trichel pulse which assumed that streamer propagates in a fixed cylindrical channel [1]. This model was extensively used in subsequent corona research [2], but its applicability is limited due to the error. Georghiou et al. [3] proposed a gas discharge model of which is two-dimensional and solved it by flux correction.
finite element method. Nonetheless, due to the high complexity of implicit flux correction finite element algorithm, the simulation is only carried out on the short gap of a few millimeters and the time scale of a few nanoseconds. Pancheshnyi et al. [4] simplified the air discharge plasma change process, and performed a cathode-directed streamer discharge in a 13 cm long gap filled with a nitrogen-oxygen mixture. Due to the influence of convection diffusion process and migration process on corona discharge process, the coefficient weight of plasma chemical reaction in corona discharge process can not be quantified, and the variation law of air composition is not detailed enough. T. Farouk et al. [5] used the argon reaction in the plasma module of COMSOL to simulate the voltage-current characteristics of the glow discharge process. In which he added Boltzmann equations to the set of hydrodynamic equations to simulate the motion of electrons, which described the law of microscopic particles with current changes in the glow discharge process, but as the chemical mechanism of the model is too simple, which makes the abnormal glow discharge occurs when the current density is too large.

In summary, the corona discharge of UHVDC transmission lines involves various particles in the air and their chemical reactions, and the physical process of the discharge is very complex. Through the existing hydrodynamic model, the particle-tracking during the corona discharge is difficult [6, 7]. On the other hand, the plasma model is only applicable to the pin-plate electrode corona discharge law, and there is still a gap in the study of the motion changes of air components during the corona discharge of UHVDC transmission lines.

In this study, the corona discharge of transmission lines is synthesized as a discharge source located at the center point of the conductor with the same corona discharge in all directions. A one-dimensional model of corona discharge of plasma coaxial cable is established, 27 chemical reactions of 12 microscopic particles in air are added based on COMSOL plasma module, the changes of electron temperature and potential on the conductor surface during the corona discharge are traced, and the corona current pulses for the corona discharge simulation of a one-dimensional transmission line are obtained. The results can provide reference and theoretical basis for the actual corona detection, and can also provide new ideas for exploring the physical process of microscopic particle changes during corona discharge.

2. The Calculated Method of Corona Discharge on Transmission Line

2.1. Basic Theory
In this work, a one-dimensional model of positive corona discharge is proposed based on hydrodynamic theory, in which photoionization and secondary electron emission processes are considered. The cross section of the coaxial cable positive corona discharge model is shown in figure 1. The inner electrode of the coaxial cable has a radius of 100um, the electrode spacing is 1cm. The steady-state process of a 10s-kV continuous discharge is applied to the inner electrode with the outer electrode grounded. The generation and transport of charged particles and how they are transformed into current-voltage characteristics are studied.
Apply a positive voltage of 60 kV to the inner conductor. It is assumed that the discharge is uniform in the radial direction. The model is a one-dimensional model in the radial direction between the electrodes, in which we assume that the gas temperature and air density are constant and the gas temperature is kept at 293.15 K. The Poisson equation for the electrostatic field is as follows:

$$\nabla \cdot \varepsilon_0 \varepsilon_r \nabla V = \rho$$  \hspace{1cm} (1)

Where $\varepsilon_0$ and $\varepsilon_r$ are vacuum and relative permittivity, respectively. V is the applied voltage, and the space charge density $\rho$ is calculated from the formula of plasma chemistry specified in the model.

The Convection–diffusion equation for the electron is:

$$\frac{\partial}{\partial t} (n_e) + \nabla \cdot [-n_e (\mu_e \cdot E) - D_e \nabla n_e] = R_e$$  \hspace{1cm} (2)

Where $n_e$, $\mu_e$, and $D_e$ are the electron density, mobility and diffusivity, respectively. $R_e$ is the electron production rate which is given by the Townsend coefficient as equation (3):

$$R_e = \sum_{j=1}^{M} x_j \alpha_j N_n |\Gamma_e|$$  \hspace{1cm} (3)

Where $x_j$ and $\alpha_j$ denote the molar and Townsend coefficient of reactant $j$, respectively. $N_n$ is the total number density of neutral particle, in $1/m^3$. $\Gamma_e$ denotes the electron flux. During DC discharge, the Townsend coefficient improves the stability of the electron flow driven by the electric field.

For non-electronic substances, the Convection–diffusion equation for each substance is expressed as equation (4):

$$\rho \frac{\partial}{\partial t} (w_k) + \rho (u \cdot \nabla) w_k = \nabla \cdot j_k + R_k$$  \hspace{1cm} (4)

Where $j_k$ denotes the diffusion flux vector, $R_k$ denotes the rate expression for substance k, $u$ denotes the mean fluid velocity, and $w_k$ denotes the mass fraction of substance k.

2.2. Boundary Conditions
The boundary condition for the electron flux is expressed as equation (5):

$$n \cdot \Gamma_e = \left( \frac{1}{2} v_{e,th} n_e \right) - \sum_{\rho} \gamma_{\rho} (\Gamma_{\rho} \cdot n)$$  \hspace{1cm} (5)

where the second term on the right-hand side is the electron gain as a result of the secondary emission effect and $\gamma_{\rho}$ denotes the secondary emission coefficient.

The discharge process is driven by a DC potential applied to the inner conductor, with the other boundary grounded. To facilitate the start of the numerical simulation, we used a step function of the transient potential to regulate the DC potential.

$$V = V_0 \tan \left( \frac{t}{\tau} \right)$$  \hspace{1cm} (6)

Take the temperature of electrons into account to describe the mechanism of electron energy generation and loss accurately, and the complete electron energy constraint equation is expressed as equation (7):
\[
\frac{3}{2} \frac{\partial (k_n T_e)}{\partial t} + \nabla \left( \frac{5}{2} k_BT_e \nabla T_e - \frac{5}{2} k_n T_e \nabla n_e \right) = j_e \cdot E - n_e \sum_k n_k \eta_k - 2n_e k_B \frac{m}{M_k} (T_e - T) \nu_{e,n}
\]  

(7)

where \( T_e \) is the electron temperature, \( n_k \) is the density of particle \( k \), \( \eta_k \) is the energy loss coefficient of collision between electron and heavy ion \( k \), \( m \) and \( M_k \) are the mass of electron and heavy ion \( k \), respectively. \( T \) is the air temperature, \( \nu_{e,n} \) is the electron energy transfer collision frequency, and the right side of equation (7) is the source term; \( j_e \cdot E \) denotes the electron energy gained by the Joule heating effect, and the last two terms denote the energy loss of elastic and inelastic collisions, respectively.

The coaxial cable model is symmetric about the anode center point, and the corona discharge is uniformly distributed on the anode surface in all directions, which can be regarded as the field obtained by rotating the line segment about the anode center for one turn in figure 2, where the circle formed by rotating around the left end point of the line segment is the anode surface, and that formed by the right point is the outer circumference of the coaxial cable.

![Figure 2. Schematic diagram of meshing of coaxial cable.](image)

2.3. Type of Air Particle Collision Reaction

The collisions between electrons and neutral molecules are mainly elastic and inelastic collisions, of which elastic collisions are accompanied by changes in electron energy, while inelastic collisions are often manifested as ionization and triggering. The collisions between electrons and neutral molecules in the corona discharge process are mainly elastic collisions, with decomposition, ionization, compounding, Convection–diffusion, photoionization process of neutral molecules. The particles present in the air ionization process are mainly \( e, O, O^+, O^+_2, O_2, O_2, N_2, N_2^+, N_2O_2^+ \), and these particles are in turn converted to each other through ionization, compounding, and adhesion reactions. In this model, 27 chemical reactions in the air discharge process are included, as shown in table 1.
Table 1. Chemical reaction processes of the main particles during air discharge.

| NO. | Reaction | Reaction coefficients | ΔE / eV |
|-----|----------|-----------------------|---------|
| R₁  | \( N₂ + e \rightarrow 2e + N₂⁺ \) | \( f(e) \) | 15.6 |
| R₂  | \( O₂ + e \rightarrow 2e + O₂⁺ \) | \( f(e) \) | 12.06 |
| R₃, R₄ | \( N₂⁺ + N₂ + M \rightarrow N₂⁺ + M \) | 5×10⁻⁴¹ |
| R₅  | \( N₂⁺ + O₂ \rightarrow O₂⁺ + 2N₂ \) | 25×10⁻¹⁶ |
| R₆  | \( N₂⁺ + O₂ \rightarrow O₂⁺ + N₂ \) | 5×10⁻⁴¹ |
| R₇  | \( 2N₂ + O₂⁺ \rightarrow N₂O₂⁺ + N₂ \) | 1.04×10⁻¹⁵T⁻⁰.⁵ |
| R₈  | \( N₂O₂⁺ + N₂ \rightarrow O₂⁺ + 2N₂ \) | 14.6T⁻⁵.³ exp(−2357/T) |
| R₉  | \( N₂O₂⁺ + N₂ \rightarrow O₂⁺ + N₂ \) | 415×10⁻¹⁰ |
| R₁₀, R₁₁ | \( O₂⁺ + O₂ + M \rightarrow O₂⁺ + M \) | 2.04×10⁻⁴⁴T⁻³.² |
| R₁₂ | \( O₂⁺ + e \rightarrow 2O₂ \) | 1.4×10⁻¹²(300/T)⁰.⁵ |
| R₁₃ | \( O₂⁺ + e \rightarrow 2O \) | 2.42×10⁻¹³(300/T) |
| R₁₄ | \( 2O₂ + e \rightarrow O₂⁺ + O₂ \) | 2×10⁻⁴¹(300/T) |
| R₁₅ | \( O₂⁺ + O₂⁻ \rightarrow 3O₂ \) | 1×10⁻¹³ |
| R₁₆, R₁₇ | \( O₂⁺ + O₂⁻ + M \rightarrow 3O₂⁺ + M \) | 2×10⁻³⁷ |
| R₁₈, R₁₉ | \( O₂⁺ + O₂⁻ + M \rightarrow 2O₂⁺ + M \) | 2×10⁻³⁷ |
| R₂₀, R₂₁ | \( O⁺ + O₂⁺ + M \rightarrow O₂ + M \) | 2.5×10⁻⁴⁶ |
| R₂₂ | \( e + N₂⁺ + N₂ \rightarrow 2N₂ \) | 6.07×10⁻³⁴Tₑ⁻².⁵ |
| R₂₃ | \( 2e + N₂⁺ \rightarrow N₂ + e \) | 5.65×10⁻³⁵Tₑ⁻⁰.⁸ |
| R₂₄ | \( O₂⁺ + O₂⁻ \rightarrow O⁺ + O₂ \) | 3.46×10⁻₂₂Tₑ⁻¹⁵ |
| R₂₅ | \( N₂⁺ + e \rightarrow e + N₂ \) | \( f(e) \) | 1.0 |
| R₂₆ | \( O₂⁺ + e \rightarrow e + O₂ \) | \( f(e) \) | 1.0 |
| R₂₇ | \( O₂⁺ + e \rightarrow O⁺ + O⁻ \) | \( f(e) \) | 3.6 |

3. Analysis of Corona Discharge Process and Corona Characteristics

In this section, a coaxial cable simulation model is established to observe the development law of electric field distribution, electron temperature distribution, and space charge distribution during positive corona discharge of transmission lines at 60 kV applied to the inner electrode, and to analyze the generation pattern of key particle components during corona discharge in detail. 12 particles and the chemical reactions between them are added to the plasma module. Compared to corona discharges added to inert gases, air corona discharges require higher voltages to break through the background gas and sustain the discharge, for two main reasons we speculate:

1) The high collision frequency of electrons in air leads to the difficult acceleration of electrons. The higher voltage provides a larger electric field, which allows electrons to move faster in the electric field.

2) More energy is required for the ionization of oxygen, so more electrons are needed to transfer energy.

3.1. Two-dimensional Distribution of Surface Electrons

Electrons are one of the main reasons for air discharges and generation of corona currents. Therefore, it is important to study the electron density distribution law during the Trichel pulse to further reveal the microphysical mechanism of corona discharge. The distribution of electron density of axial at six different moments during a Trichel pulse shows in figure 3.
Every time a positive voltage is applied to the anode of the coaxial cable, the electrons move rapidly toward the cable under the positive polarity electric field. During the movement, electrons constantly collide with the air molecules inside the cable to ionize it, resulting in more electrons and positive ions. The quantity of electrons is increasing, forming an electron avalanche. The simulation process (a) to (b) in figure 3 is an electron avalanche. The critical interface between the red area and the blue area is called the ionospheric boundary, the red area is the ionization region, and the blue region is the migration region. The electrons gathered on the surface of the coaxial cable enter the interior cable due to the action of the electric field, while the positive ions stay away. As in figure 3(b), the red area gradually becomes smaller while the blue one gradually becomes larger. When the electric field formed by the aggregation of positive ions and generated by the high voltage of the wire reach equilibrium, the electron movement is maintained in an equilibrium state, and the area of the red and blue regions remain unchanged. When the second electron avalanche occurs, the number of positive ions gradually increases, and the inhibition of electrons gradually increases. (c) and (d) in figure 3 demonstrate this process, with the red region expanding outward and the blue one being compressed until it finally drives the discharge to stop. As time goes by, the positive ions gradually diffuse under the action of electric field leading to a gradual weakening of the reverse electric field. The next corona discharge will occur when the conditions for the second discharge are met. Figure 3(e), (f) is the process of the second discharge. The process of corona discharge is repeated continuously to form multiple corona current pulses.

3.2. Axial Distribution of Electron Density in the Discharge Gap

Figure 4 demonstrates the axial distribution curve of electron density in the discharge gap at four different moments from the beginning to the end of the corona discharge. At the initial moment of discharge, electrons are uniformly distributed in the discharge gap, and as the anode discharge starts, electrons around the cable and near the cathode move to the inside of the wire under the action of field strength, so the electron density on the surface of the wire and near the cathode shows a gradually
decreasing trend. In the middle of the anode and cathode, which is the migration zone, the electron density appears as a maximum, which is due to the fast-moving electrons colliding with neutral molecules such as nitrogen and oxygen in the air, ionizing them and forming more electrons and positive ions, and the number of electrons keeps increasing, forming an electron avalanche. In this process, the attachment and compound reaction between electrons and ions makes the number of free electrons decreasing.

![Electron density distribution](image)

**Figure 4.** Axial distribution curve of electron density in the discharge gap.

### 3.3 Development Law of Electron Temperature and Potential

The electron temperature is the most direct reflection of the energy possessed by the electrons themselves. The electrons convert electric energy obtained from the electric field into their own thermal and kinetic energy, and transfer it to the neutral molecule during the collision to make it ionize. The variation of electron temperature is of great reference significance for describing the state change of microscopic particles during corona discharge. Figure 5 (a) shows the electron temperature distribution curve along the axis, and it can be found that the electron temperature is almost close to zero at the inner conductor, which is due to the absorption of electrons into the conductor. In the ionization region, the electrons rapidly absorb the energy of the field and their own temperature rises sharply and is maintained continuously. Near the cathode, the number of electrons decreases and the electron temperature drops to the bottom. Figure 5 (b) shows the variation curve of the potential along the axial direction, it can be found that there is a downward trend in the potential from the inner conductor to the grounded end of the cable.
3.4. Corona Current Pulse

Figure 6 shows a corona current pulse diagram obtained from the simulation of corona discharge of a coaxial cable. At the beginning of the discharge for a few nanoseconds, the electrons move rapidly to produce a large current, and the corona current surge to 1mA, reach the peak of the current corona. After that, the corona current gradually decreased. The total corona current has a pulse width of about 120ns and a pulse peak of 0.1mA.

4. Conclusion

In this work, a simplified model of the discharge of a transmission line combining fluid dynamics and plasma is proposed. The macroscopic changes of corona discharge in transmission lines are simulated using Poisson's equation and convection-diffusion equation. The model incorporates 12 air particles and their 27 microscopic chemical change reactions, and the two-dimensional electron density distribution map of the conductor surface and the density change curves of electrons and ions with time and space are obtained. Meanwhile, the following conclusions are obtained.

1) With the beginning of anode discharge, electrons around the cable and near the cathode move to the inner conductor so the surface electron density of the conductor shows a decreasing trend. The maximum electron density appears in the migration zone between cathode and anode.
2) The temperature of the electron shows a rapid increase in the axial direction, and after maintaining it for a period of time, it quickly reaches the peak and then drop to the bottom.
3) The potential curve shows a downward trend from the inner conductor to the grounded end of the cable.
4) The corona current pulse spick to 1mA and gradually descend into the bottom.
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