

Article

Study on the Characteristics of Positive and Negative Corona Discharge of an Independent Lightning Rod Under Different Background Electric Field Amplitude

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Abstract

Corona discharge at the tip of buildings in a thunderstorm environment is an important factor causing changes in the near-ground electric field, but the influence of a quadratic growth law and quantitative research on the parameters is still rare. Therefore, based on the three-dimensional corona discharge model, this paper studies the influence of positive and negative symmetrical triangular wave electric fields with different amplitudes on the corona discharge of an independent lightning rod. Studies have shown that the corona current is synchronized with the peak of the background electric field. Studies have shown that the corona current is synchronized with the peak of the background electric field. When the polarity of the electric field changes from positive to negative, the positive charge accumulated in the positive half-cycle promotes the subsequent negative corona, so the negative corona starts in advance when the polarity reverses. Compared with unipolar discharge, the amplitude of the negative current and the number of negative charges have significantly improved. However, due to the counteraction of neutralization between positive and negative charges, the total corona charge is at a low level, which shows a net negative polarity result. The corona current and the amount of charge increase nonlinearly with an increase in the background electric field amplitude. Under the symmetrical triangular wave electric field, the quantitative fitting relationship between the peak value of the negative corona current in the second half-cycle and the amount of charge is established for the 5 m high independent lightning rod, which is $I^- = -0.0532 - 0.153 E - 0.0682 E^2$, $Q^- = -3.18 \times 10^{-3} + 7.762 \times 10^{-4} E - 4.671 \times 10^{-5} E^2$, respectively. The increase in the background electric field amplitude will aggravate the disturbance of the corona discharge to the near-surface electric field. When the direction of the electric field has reverted to zero, the existence of the space charge will lead to a significant change in the strength and polarity of the ground electric field. When the thunderstorm background electric field changes from positive to negative, the corona effect reverses the polarity of the ground electric field in advance, and the larger the peak value of the background electric field, the larger the advance. The corona interference mechanism revealed by this study can provide an important reference for correcting the electric field monitoring data and improving the accuracy of lightning warnings.

Keywords: polarity reversal of electric field; corona charge; corona current; three-dimensional numerical simulation; electric field amplitude



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1. Introduction

Lightning is a natural phenomenon with destructive, short-term and sudden characteristics, which poses a serious threat to people's lives, property and social infrastructure. In the thunderstorm environment, the disturbance of the near-surface electric field mainly comes from the corona discharge process at the tip of a building, and the intensity of the discharge directly depends on the amplitude of the background electric field. However, the current research on how the electric field amplitude affects the positive and negative corona discharge is still insufficient, and it is difficult to make an accurate prediction of lightning discharge.

Tip corona discharge refers to the partial discharge induced when the surface field strength of the tip exceeds the critical value of the air breakdown. According to the polarity difference, it can be divided into two types: positive and negative corona discharge. In view of the corona discharge characteristics, scholars have carried out a large number of experimental and simulation studies. Qie et al. [1] studied the electrical characteristics of thunderstorms in plateau areas at different altitudes and found that the difference in atmospheric electric fields under thunderstorm clouds was mainly related to the charge composition of the clouds. The one-dimensional tip corona ion diffusion model was constructed by Aleksandrov et al. [2], and the corona discharge characteristics of the tip of the grounded object were discussed by means of analysis and numerical methods. Based on the existing results of Aleksandrov et al. [3,4], Becerra [5] constructed a two-dimensional axisymmetric corona model to simulate the discharge dynamics and corona inception characteristics under a symmetrical tip configuration. Guo et al. [6] constructed a three-dimensional variable grid model to explore the significant influence of the wind field on the positive corona discharge intensity and the local electric field distribution of buildings. Beccera et al. [7] used a two-dimensional numerical model as a tool to explore the specific effects of positive and negative space charges on the electric field. Luo [8] clarified the variation patterns of unipolar positive and negative corona discharges with the increase and decrease of electric field intensity by combining experimental and numerical methods. Through the direct measurement of the discharge process of the ground needle electrode, Yosho et al. [9] established a quantitative relationship between the tip corona current and the ground electric field intensity, and they described the evolution characteristics of the current. Feng [10] studied the mechanism and application of negative corona discharge in different environments through an improved needle-plate corona discharge model. Zhu et al. [11] used the two-dimensional finite element method to carry out numerical simulation research and observed that the corona current generated by the metal tip is proportional to the total electric field at the tip. However, most of the above studies focus on the constant electric field or unipolar electric field, and there is still a lack of systematic research on how the polarity reversal process affects the positive and negative corona discharges. In particular, the promotion or inhibition effect of the heteropolar charge accumulated in the first half-cycle on the subsequent discharge under different background electric field amplitudes has not been fully revealed.

Accordingly, utilizing a 3D bipolar corona discharge framework, this paper simulates the corona discharge characteristics of the independent lightning rod under different background electric field amplitudes and analyzes the influence of the electric field amplitude on the corona current, charge and spatial electric field distribution, which provides a theoretical basis for the prediction of the tip discharge behavior of buildings in thunderstorms.

2. Model Introduction and Parameter Setting

The simulation domain of this paper is a three-dimensional space area of $500\text{ m} \times 500\text{ m} \times 500\text{ m}$. The simulation time is 4 s, the time resolution is 0.0004 s,

the height of the independent lightning rod is 5 m, and the tip radius is set to 0.0005 m. In the actual observation, the electric field in the thunderstorm cloud is complex and changeable and will be affected by the charge in the cloud. It usually has the characteristics of asymmetry, multi-pulse and randomness, and a polarity reversal often occurs [12,13]. In order to study the influence of electric field polarity reversal and electric field amplitude change on corona discharge during thunderstorms, this paper uses positive and negative symmetric triangular waves as the simplified form of the background electric field, and the waveform is set with reference to Guo Fengxia et al. [13]. It is positive in 0–2 s and negative in 2–4 s, and the amplitudes are 5, 10, 15, 20 and 25 kV/m, respectively. The change trend of the background electric field, E_b , is shown in Figure 1. Based on the main physical characteristics of the actual thunderstorm environment, the above settings create conditions for further analysis of the interaction between the polarity reversal of the electric field and the evolution of the corona discharge.

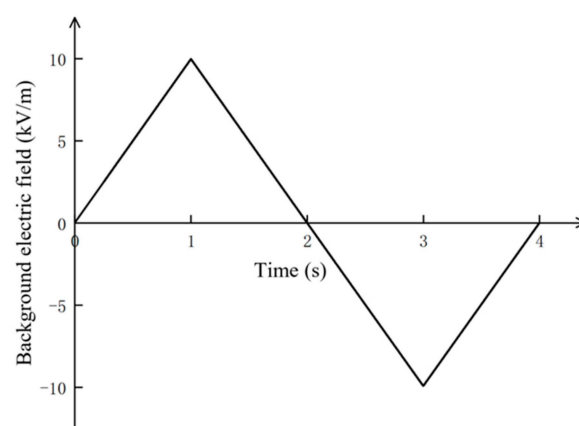


Figure 1. The variation trend of the background electric field, E_b , of the triangular wave with positive and negative symmetry.

First, the tip electric field threshold E_{cor} is calculated by the Peek formula [14]. The specific mathematical relationship is shown in Formula (1):

$$E_{cor} = 27.2 \left(1 + \frac{0.54}{\sqrt{r_{rod}}} \right) \quad (1)$$

Here, r_{rod} is the radius of the curvature of the building tip, and its value is 0.5 mm. The calculated value of E_{cor} is 3.75×10^6 V/m.

Based on the assumption proposed by Kaptzov [15–17], the electric field intensity after the tip surface corona onset will be stable at the corona onset threshold E_{cor} level, as expressed in Equation (2):

$$E_{tip}(t_0) \geq E_{cor} \quad (2)$$

Here, $E_{tip}(t_0)$ is the electric field value of the tip surface after time t_0 .

The Peek formula provides the threshold for the initial electric field of the tip corona discharge, which is the core criterion of the three-dimensional positive and negative corona discharge model. Combined with the Kaptzov hypothesis, this law limits the tip electric field after the corona onset to near the threshold, unifies the corona onset criteria under different background electric field amplitudes, and reveals the promoting effect of the first half-cycle charge on the second half-cycle discharge during the polarity reversal process. In addition, the Peek formula provides physical constraints for the fitting relationship between the corona current and electric field amplitude, which ensures the applicability and reliability of the model.

After the tip surface enters the corona onset stage, the corona charge begins to exhibit convection and diffusion behavior. From the perspective of microscopic particles, this behavior is jointly participated by positive and negative polar ions and neutral aerosol particles, including four processes: diffusion movement caused by an uneven distribution of ion (particle) concentration, mutual neutralization of heteropolar ions, migration movement driven by electric field force or wind force, the adsorption effect of aerosol particles on positive and negative small ions. The convection–diffusion equation describing this series of processes is shown in Equation (3):

$$\begin{aligned}
 \frac{\partial n_+}{\partial t} &= D \cdot \nabla^2 n_+ - k_{n_+ N_0} \cdot n_+ \cdot N_0 - k_{n_+ N_-} \cdot n_+ \cdot N_- - \alpha \cdot n_+ \cdot n_- - \nabla \cdot \left(n_+ \cdot \mu_{n_+} \cdot \vec{E} \right) \\
 \frac{\partial n_-}{\partial t} &= D \cdot \nabla^2 n_- - k_{n_- N_0} \cdot n_- \cdot N_0 - k_{n_- N_+} \cdot n_- \cdot N_+ - \alpha \cdot n_+ \cdot n_- - \nabla \cdot \left(n_- \cdot \mu_{n_-} \cdot \vec{E} \right) \\
 \frac{\partial N_+}{\partial t} &= D \cdot \nabla^2 N_+ + k_{n_+ N_0} \cdot n_+ \cdot N_0 - k_{n_- N_+} \cdot n_- \cdot N_+ - \nabla \cdot \left(N_+ \cdot \mu_{N_+} \cdot \vec{E} \right) \\
 \frac{\partial N_-}{\partial t} &= D \cdot \nabla^2 N_- + k_{n_- N_0} \cdot n_- \cdot N_0 - k_{n_+ N_-} \cdot n_+ \cdot N_- - \nabla \cdot \left(N_- \cdot \mu_{N_-} \cdot \vec{E} \right) \\
 \frac{\partial N_0}{\partial t} &= D \cdot \nabla^2 N_0 + k_{n_- N_+} \cdot n_- \cdot N_+ + k_{n_+ N_-} \cdot n_+ \cdot N_- - k_{n_+ N_0} \cdot n_+ \cdot N_0 - k_{n_- N_0} \cdot n_- \cdot N_0
 \end{aligned} \tag{3}$$

Here, n_+ and n_- are the concentrations of positive and negative small ions, respectively, N_+ and N_- are the concentrations of positive and negative large ions, respectively. N_0 is the concentration of neutral aerosol particles, the turbulent diffusion coefficient of ions (particles) $D = 1 \text{ m}^2 \cdot \text{s}^{-1}$, and μ is the ion mobility. The ion mobility is as follows: the mobility of small positive ions is $\mu_{n_+} = 1.5 \times 10^{-4} \text{ m}^2 \cdot (\text{V} \cdot \text{s})^{-1}$; the mobility of small negative ions is $\mu_{n_-} = -2 \times 10^{-4} \text{ m}^2 \cdot (\text{V} \cdot \text{s})^{-1}$; and the mobility of large positive ions is $\mu_{N_+} = 1.5 \times 10^{-6} \text{ m}^2 \cdot (\text{V} \cdot \text{s})^{-1}$. The mobility of large anion is $\mu_{N_-} = -2 \times 10^{-6} \text{ m}^2 \cdot (\text{V} \cdot \text{s})^{-1}$; the adsorption rate of aerosol particles to positive small ions is $k_{n_+ N_0} = 2.9 \times 10^{-12} \text{ m}^3 \cdot \text{s}^{-1}$; the adsorption rate of aerosol particles to negative small ions is $k_{n_- N_0} = 3.5 \times 10^{-12} \text{ m}^3 \cdot \text{s}^{-1}$; the recombination coefficient of small positive ions to large negative ions is $k_{n_+ N_-} = 5 \times 10^{-12} \text{ m}^3 \cdot \text{s}^{-1}$; the recombination coefficient of small negative ions to large positive ions is $k_{n_- N_+} = 6 \times 10^{-12} \text{ m}^3 \cdot \text{s}^{-1}$; the recombination coefficient of small positive ions and small negative ions is $\alpha = 1.6 \times 10^{-12} \text{ m}^3 \cdot \text{s}^{-1}$; t represents time; and E represents the environmental electric field [7].

Figure 2 is a schematic diagram of the corona discharge region, and an upward background electric field E_b is formed between the thunderstorm cloud and the ground. Due to the tip effect, the surface electric field intensity E_{tip} of the independent lightning rod on the ground is significantly enhanced. When the corona onset threshold, E_{cor} , is reached, the corona discharge occurs at the tip, and the positive ions move in the direction of the cloud under the action of the electric field and accumulate above the tip to form a space charge layer. As the background electric field decreases, the E_{tip} decreases. When it is lower than the corona onset threshold, E_{cor} , the tip corona discharge stops. When the polarity of the thunderstorm electric field is reversed and increased in reverse, the residual positive charge will significantly enhance the tip electric field, resulting in the occurrence of negative corona in advance, and the negative ions generated by the negative corona will neutralize the residual positive charge.

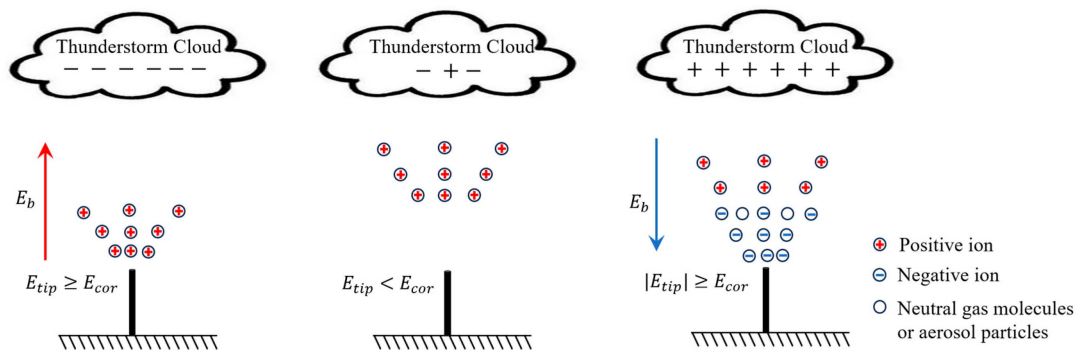


Figure 2. Chart of corona discharge.

In this paper, the upper boundary of the three-dimensional simulation domain, the earth and the surface of the building are the first type of boundary with fixed potential, and the other four sides are the second type of boundary with zero flux. In the calculation, the over-relaxation iteration method is used to determine the potential of the global grid point, and then the electric field value is obtained from the spatial change rate of the potential according to Formula (4):

$$E = -\nabla\varphi \quad (4)$$

where E is the electric field value.

After ignoring the effect of the free charge in the thunderstorm environment, the near-surface atmospheric electric field can be equivalent to a vertical uniform field. At this time, the determination of the three-dimensional space grid potential is attributed to the solution of the Poisson equation, and the calculation formula is Equation (5):

$$\nabla^2\varphi = -\frac{\rho}{\varepsilon_0} \quad (5)$$

Here, ∇ is the Laplace operator, φ is the potential for the corona charge density, ε_0 is the vacuum capacitance rate (vacuum dielectric constant), taking $8.854 \times 10^{-12} \text{ F}\cdot\text{m}^{-1}$.

The volume density of the corona charge can be calculated by the concentration of the small and large ions with positive and negative polarity. According to Formulas (4) and (5), the calculation formula of the electric field and the potential can be further obtained. The calculation formula is shown in Formula (6):

$$\nabla^2\varphi = -\frac{e_0(n_+ + N_+ - n_- - N_-)}{\varepsilon_0} \quad (6)$$

Here, e_0 is the amount of elementary charge, and ε_0 is the vacuum capacitance rate.

In order to test the validity of the model, the observation data of Yosho et al. [9] are used as a reference. The experimental system includes a grounding needle electrode with a total height of 5 m and a top-fixed 1.5 m platinum wire. The corona current and the near-ground electric field signal are monitored by a coaxial cable about 10 m away from the electrode. The simulation conditions are set as follows: the background electric field of the positive and negative symmetrical sawtooth wave with an amplitude of $\pm 10 \text{ kV/m}$, the side length of the simulation domain is 500 m, the total calculation time is 4 s, the time resolution is 0.0004 s, and the building height is 5 m. Figure 3a is the measured data, and Figure 3b is the background field intensity, tip corona current and near-ground electric field variation process output by the model. The comparison results show that the simulated corona current reaches the peak at the peak of the background electric field, and there is a time delay in the current response during the polarity conversion. The overall change rule is consistent with the measured record. The peak difference is mainly due to the

difference between the shielding loss of the coaxial cable and the conductivity of the tip material. The above comparison confirms that the model can effectively describe the basic characteristics of corona discharge and has good credibility. For the specific calculation method and verification details of the model, see Wang Zhaoxia et al. [18].

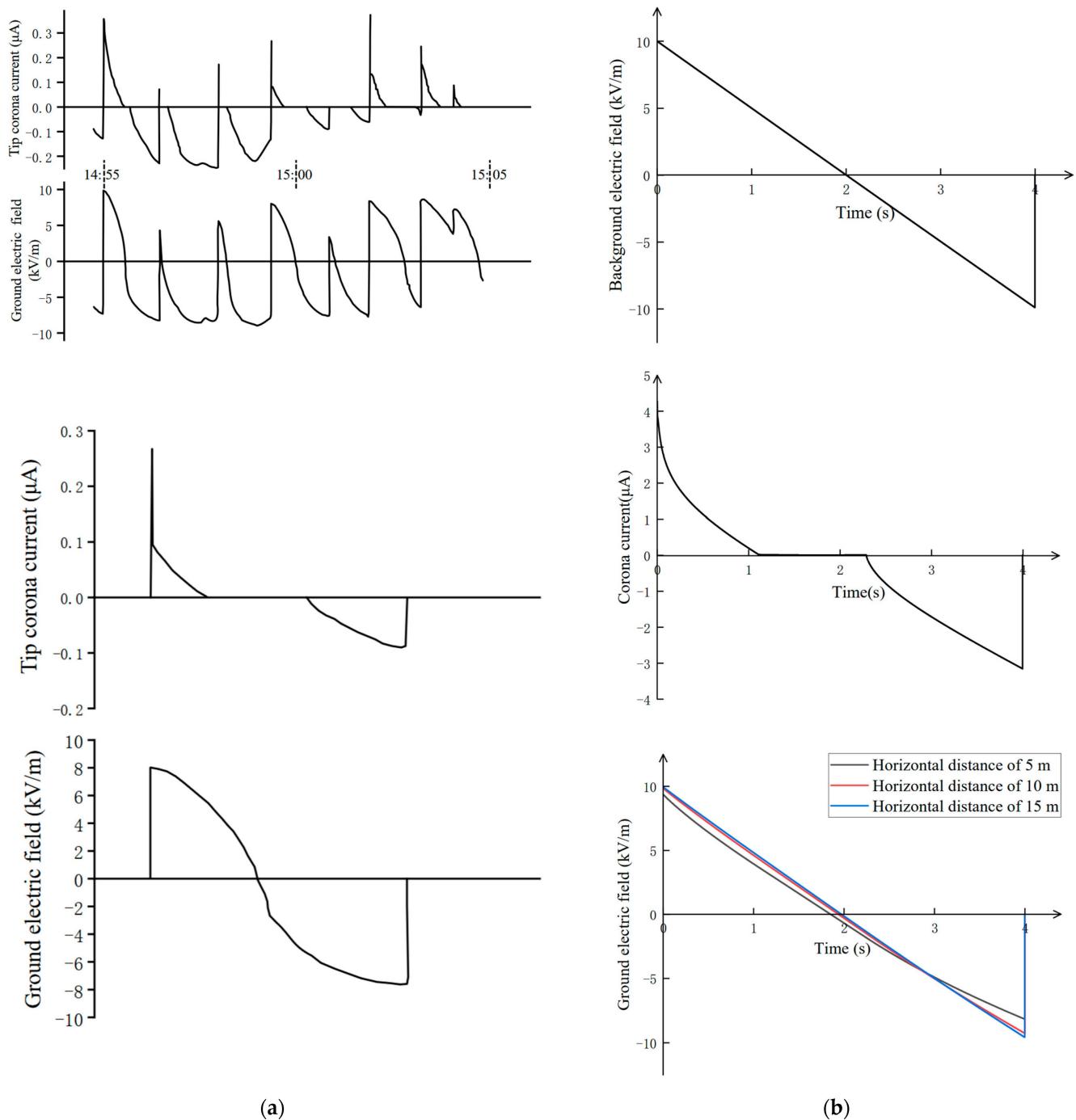


Figure 3. This shows the comparison between the model and the observation results. (a) Measured data and (b) simulation results of this model.

3. Simulation Results and Analysis

3.1. Variation Characteristics of Positive and Negative Corona Current of an Independent Lightning Rod Under Different Electric Field Amplitudes

In this section, the corona current variation characteristics of an independent lightning rod with a height of 5 m under different amplitudes of positive and negative symmetric triangular wave background electric fields are compared, as shown in Figure 4.

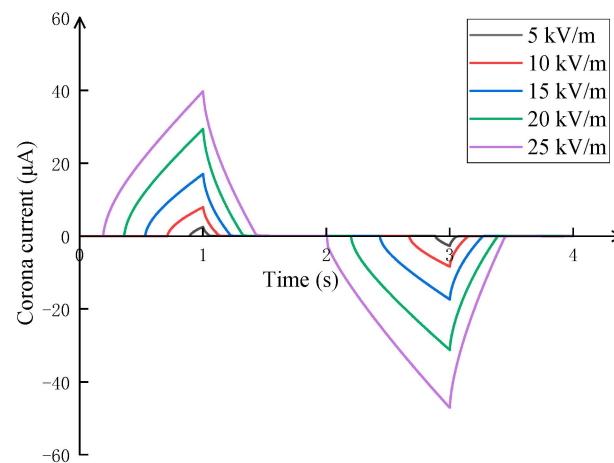


Figure 4. The variation trend of the corona current under different electric field amplitudes.

According to the results of Figure 4, the influence of the change in electric field amplitude on the corona current at the tip of the building shows a certain regularity. Under the same background electric field waveform and lightning rod height, the corona current increases with the increase in electric field amplitude. The peak values of the positive and negative currents show a similar growth trend, and the growth rate increases with the increase in electric field amplitude, indicating that the growth rate of the corona current is faster under the action of a strong electric field. When the electric field amplitude is 5 kV/m, the generation time of the negative corona current is 2.883 s, corresponding to the background electric field of a thunderstorm cloud, which is -4.415 kV/m. The unipolar corona discharge needs to experience 0.8904 s, and the electric field strength must reach 4.452 kV/m. In contrast, the corona electric field inception of the positive and negative polarity models is reduced by 37 V/m, and the discharge time is advanced by 0.0074 s. When the electric field amplitude increases to 25 kV/m, the negative corona current is generated at 2.006 s, and the corresponding background electric field is only -0.15 kV/m. The unipolar model needs 0.1781 s, and the electric field intensity needs to reach 4.452 kV/m to discharge. The corona electric field inception of the positive and negative polarity model is reduced by 4.605 kV/m, and the discharge time is increased by 0.1721 s. The positive corona charge left in the first half-cycle forms a significant positive drive to the negative corona discharge in the second half-cycle, and the driving intensity increases synchronously with the increase in the background electric field amplitude. Moreover, the increase in the background electric field amplitude also leads to the early onset of the negative corona current. Compared with the amplitude of 5 kV/m, the discharge advance time at the amplitude of 25 kV/m increased by 0.1647 s.

The physical mechanism of the increase in the negative corona current is that when the polarity of the electric field is reversed, the electric field generated by the positive space charge retained in the first half-cycle is superimposed with the background electric field in the same direction, so that the total field strength of the tip surface is significantly higher than that of the background field. The enhancement of the local electric field directly leads to the intensification of the ionization process and a substantial increase in the ion

production rate, which significantly increases the amplitude of the negative corona current in the second half-cycle. The experiments of Kyselová D and Dagmar Štěpánová [19,20] show that the corona discharge has the highest intensity at the tip of the electrode during a negative pulse discharge, so the radiation dose increases significantly at the tip, while there is no statistical increase in the grounding electrode in the lateral position. This spatial distribution feature is highly consistent with the tip-concentrated corona charge distribution model constructed in this paper. In addition, the negative discharge X-ray radiation observed in the experiment is significantly more than the polarity asymmetry of the positive discharge, which is also closely related to the positive and negative corona current asymmetry revealed in this paper.

Under the symmetrical triangular wave background electric field waveform, the fitting curve between the corona current peak and the electric field amplitude is shown in Figure 5. Among them, the fitting curve reached a significant level of 0.05.

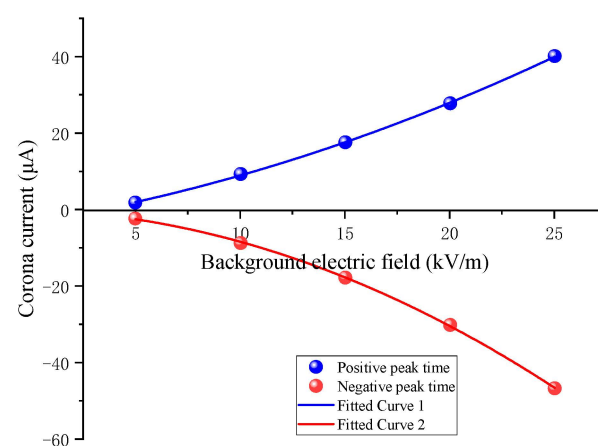


Figure 5. The fitting curve of the corona current peak and the background electric field amplitude.

Figure 5 shows that the peak value of the corona current increases nonlinearly with the amplitude of the background electric field. Although the current trends at the positive and negative peaks are roughly the same, the peak value of the negative corona current is always greater than the positive current, and its growth rate is significantly ahead. With the increase in background field strength, the increase in corona current is further strengthened, and the outburst degree and change rate of the negative current peak are improved. Accordingly, the background electric field amplitude has a significant dominant effect on the tip corona current.

From the fitting curve, the fitting formula between the corona current peak I and the electric field amplitude E under the two background electric field waveforms when the height of the independent lightning rod is 5 m is shown in Formula (7):

$$I = \alpha_1 + \beta_1 E + \gamma_1 E^2 \quad (7)$$

α_1 , β_1 and γ_1 are constants. The specific values of α_1 , β_1 , γ_1 and R^2 are shown in Table 1.

Table 1. The specific values of α_1 , β_1 and γ_1 and R^2 .

Type of Peak Current	α_1	β_1	γ_1	R^2
Positive peak I^+	-3.335 ± 0.604	0.890 ± 0.0921	0.0336 ± 0.00301	0.99965
Negative peak I^-	-0.0532 ± 0.753	-0.153 ± 0.115	-0.0682 ± 0.00375	0.99961

Here, I is the peak value of the corona current of the symmetrical triangular wave when the height of the independent lightning rod is 5 m, and the unit is μA . α_1 shows that the corona current should be zero when the background electric field is zero, in theory. The small non-zero value obtained by fitting is only a numerical deviation and has no practical or physical significance. β_1 is a linear response coefficient, which reflects the basic contribution of ion migration flow to the current under a weak electric field, and its size is related to tip geometry, ion mobility and other factors. γ_1 is the nonlinear response coefficient, which reflects the nonlinear growth trend of the current with the increase in the electric field. When the electric field is strong, the residual heteropolar charge in the first half-cycle produces positive feedback to the local electric field at the tip, and the ionization rate and ion yield are greatly increased, resulting in the current growth exceeding the linearity. The γ_1 of the negative corona is negative due to the current symbol agreement, and its absolute value increases superlinearly with the electric field. E is the amplitude of the background electric field, and its unit is kV/m . The application scope of the formula is that the height of the independent lightning rod is 5 m, and the background electric field amplitude is 5–25 kV/m .

Under different waveform conditions, the negative corona current peaks calculated by the positive and negative polarity model and the unipolar model are not consistent. To this end, this paper further compares the evolution of the negative corona current under the two models, and the relevant comparison results are shown in Figure 6.

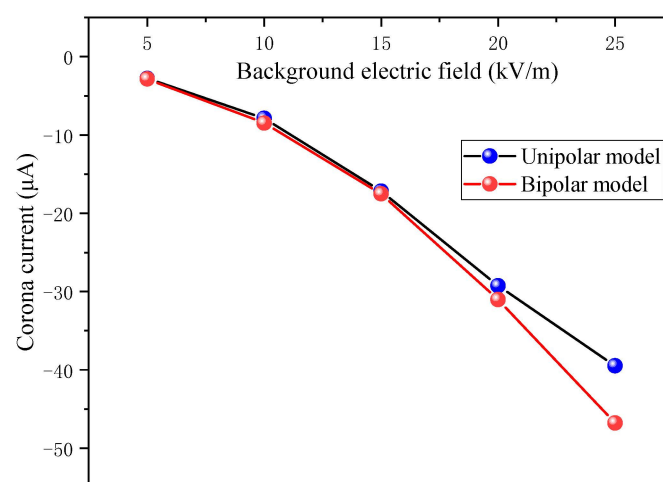


Figure 6. The change trend of the negative corona current peak in the positive and negative polarity model and the unipolar model.

Figure 6 shows the comparison between the positive and negative polarity model and the unipolar corona discharge model during the evolution of the negative corona current peak. Although both of them show an increasing trend of negative current peak with the background electric field amplitude, the negative current peak predicted by the positive and negative polarity models is always higher than that predicted by the unipolar model under the same field strength. The reason is that in the process of electric field polarity reversal, the positive corona charge accumulated in the first half-cycle plays a boosting role in the generation of negative corona current in the second half-cycle, while the unipolar model lacks this effect. Figure 6 further shows that the strength of the boosting effect is positively correlated with the amplitude of the electric field.

In summary, there is a quadratic relationship between the corona current peak and the background electric field amplitude, and this law is not affected by the first half-cycle discharge. However, compared with the first half-cycle or unipolar condition, the

peak value of the corona current in the second half-cycle increases faster and higher with the increase in field strength, and the influence of the field strength is also greater. In addition, the existence of the charge in the first half-cycle makes the background electric field threshold required for the corona onset in the second half-cycle decrease, and the discharge onset time moves forward accordingly.

3.2. Variation Characteristics of Positive and Negative Corona Charge of an Independent Lightning Rod Under Different Electric Field Amplitudes

The total amount of corona charge release changes with the amplitude of the background electric field. In this section, the dynamic response of the corona charge of an independent lightning rod with a height of 5 m under the background electric field of various positive and negative symmetrical triangular waves is compared, and the results are shown in Figure 7.

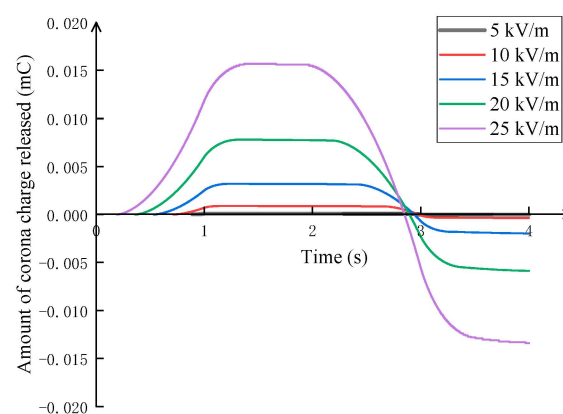


Figure 7. The variation trend of the corona charge under different amplitudes.

According to the analysis results of Figure 7, under the condition that the height of the independent lightning rod is fixed, the amount of charge released increases significantly with the increase in the background electric field amplitude. This phenomenon shows that the intensity of the background electric field has an important influence on the charge release process, especially under the action of a strong electric field, where the accumulation and release of charges become more significant. When the background electric field amplitude reaches 25 kV/m, the increase in released charge is particularly significant, indicating that the strong electric field can enhance the corona discharge at the tip of the independent lightning rod, so that more charge accumulates and is released.

By analyzing the peak value of corona charge release under the background electric field waveform of a symmetrical triangular wave, the fitting curve between the peak value of the corona charge and the amplitude of the background electric field can be observed, as shown in Figure 8.

It can be seen from Figure 8 that there is a nonlinear relationship between the peak value of the corona charge and the background electric field amplitude, and the peak value of the corona charge increases with the increase in the amplitude of the background electric field. At the same independent lightning rod height, the change rate of the peak value of the positive corona charge is significantly higher than that of the peak value of the negative corona charge, mainly because when the positive and negative electric fields are reversed, the positive corona charge and the negative corona charge are neutralized, thereby reducing the total corona charge.

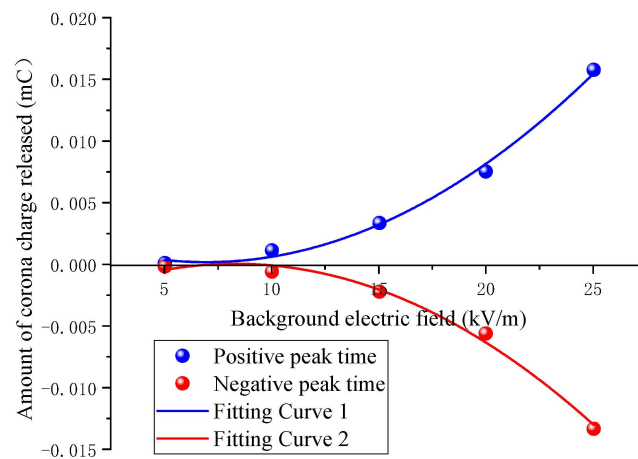


Figure 8. The fitting curve of the corona charge peak value and the background electric field amplitude.

From the fitting curve, the fitting formula between the corona charge peak, Q , and the background electric field amplitude, E , when the height of the independent lightning rod is 5 m, is shown in Formula (8):

$$Q = \alpha_2 + \beta_2 E + \gamma_2 E^2 \quad (8)$$

Here, α_2 , β_2 and c are constants. The specific values of α_2 , β_2 and γ_2 and R^2 are shown in Table 2.

Table 2. The specific values of α_2 , β_2 , γ_2 and R^2 .

The Peak Type of Corona Charge Quantity	α_2	β_2	γ_2	R^2
Positive peak Q_1^+	$(2.43 \pm 1.35) \times 10^{-3}$	$(-6.497 \pm 2.058) \times 10^{-4}$	$(4.677 \pm 0.672) \times 10^{-5}$	0.99027
Negative peak Q_1^-	$(-3.18 \pm 1.5) \times 10^{-3}$	$(7.762 \pm 2.287) \times 10^{-4}$	$(-4.671 \pm 0.747) \times 10^{-5}$	0.98352

Here, Q is the peak value of the corona charge corresponding to the background electric field of a symmetrical triangular wave when the height of the independent lightning rod is 5 m. The unit is mC, and α_2 shows that the charge should be zero when the theoretical background electric field is zero. The small non-zero value obtained by the actual fitting is only a numerical deviation and has no physical meaning. β_2 is a linear response coefficient, which reflects the approximate linear change in charge with the electric field under a weak electric field. γ_2 is a nonlinear response coefficient, which reflects the superlinear growth caused by the positive feedback of space charge under a strong electric field. The negative corona $\gamma_2 < 0$ is caused by the charge symbol agreement, and the absolute value of the charge also increases superlinearly with the electric field. E is the background electric field amplitude, and the unit is kV/m. The applicable range of this formula is that the height of the independent lightning rod is 5 m, and the background electric field amplitude is 5–25 kV/m. However, the actual thunderstorm background electric field is mostly an asymmetric waveform. The larger the amplitude of the positive half-cycle electric field, the higher the corona current and charge release, and the stronger the promotion effect of the heteropolar charge accumulated in the first half-cycle on the discharge in the second half-cycle, which leads to an earlier corona onset and a higher current of the negative corona, but the neutralization reduces the total net charge.

The positive and negative polarity model and the unipolar model have different negative corona charge peaks under different background electric field amplitudes. Therefore,

the change trends of the negative corona charge under the two models are compared. The change trend is shown in Figure 9.

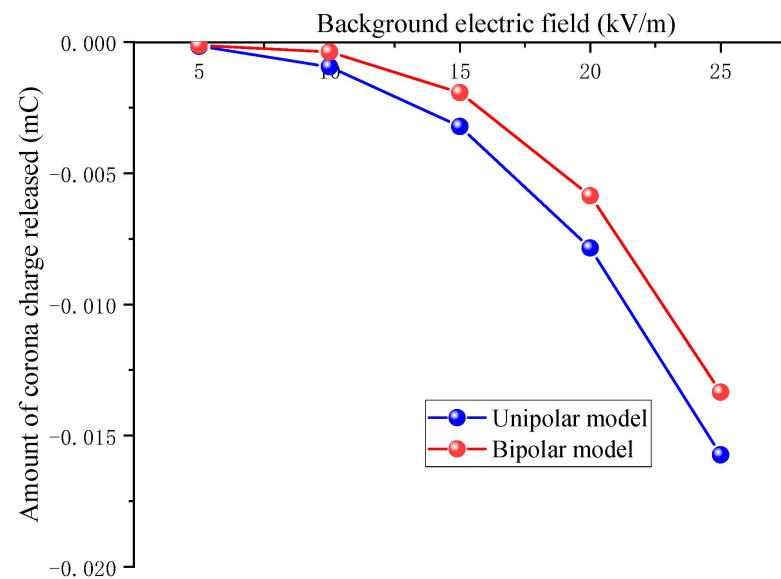


Figure 9. The change trend of the negative corona charge peak of the positive and negative polarity model and the unipolar model.

It can be seen from Figure 9 that under the background electric field of a symmetrical triangular wave, compared with the unipolar corona discharge model, with an increase in the background electric field amplitude, the charge amount of the unipolar model increases obviously, while the charge amount of the positive and negative polarity models increases slightly. The main reason is that when the electric field is reversed, the positive corona charge generated in the positive half-cycle and the negative corona charge generated in the second half-cycle produce a neutralization effect, which reduces the amount of corona charge. However, there is no neutralization effect in the unipolar corona discharge model simulation, so the amount of corona charge generated is more than that of the positive and negative corona discharge model.

3.3. The Influence of an Independent Lightning Rod on the Electric Field Under Different Background Electric Field Amplitudes

Different background electric field amplitudes will lead to changes in the spatial electric field distribution, which will affect the ground electric field and then affect the measurement results of the atmospheric electric field instrument. In this section, the positive and negative symmetrical triangular wave is selected as the background electric field. The height of the independent lightning rod is 5 m, and the amplitude of the background electric field is 15 kV/m and 25 kV/m. For example, 10–11 is the spatial electric field distribution map of each time point under different background electric field amplitudes with or without corona.

As shown in Figures 10 and 11, when corona discharge occurs, the spatial electric field distribution maintains a similar symmetry to that without corona, but the tip electric field intensity is enhanced. With the increase in the background electric field amplitude, the tip electric field also increases and reaches the maximum value at the positive and negative peaks. However, the tip electric field strength at the negative peak is lower than that at the positive peak. When the background electric field is reduced to zero, the tip electric field is weakened, forming a negative polarity feature, and the sky is positive. When the

background electric field increases to zero, the tip electric field is weakened, forming a positive polarity feature, and the sky is negative.

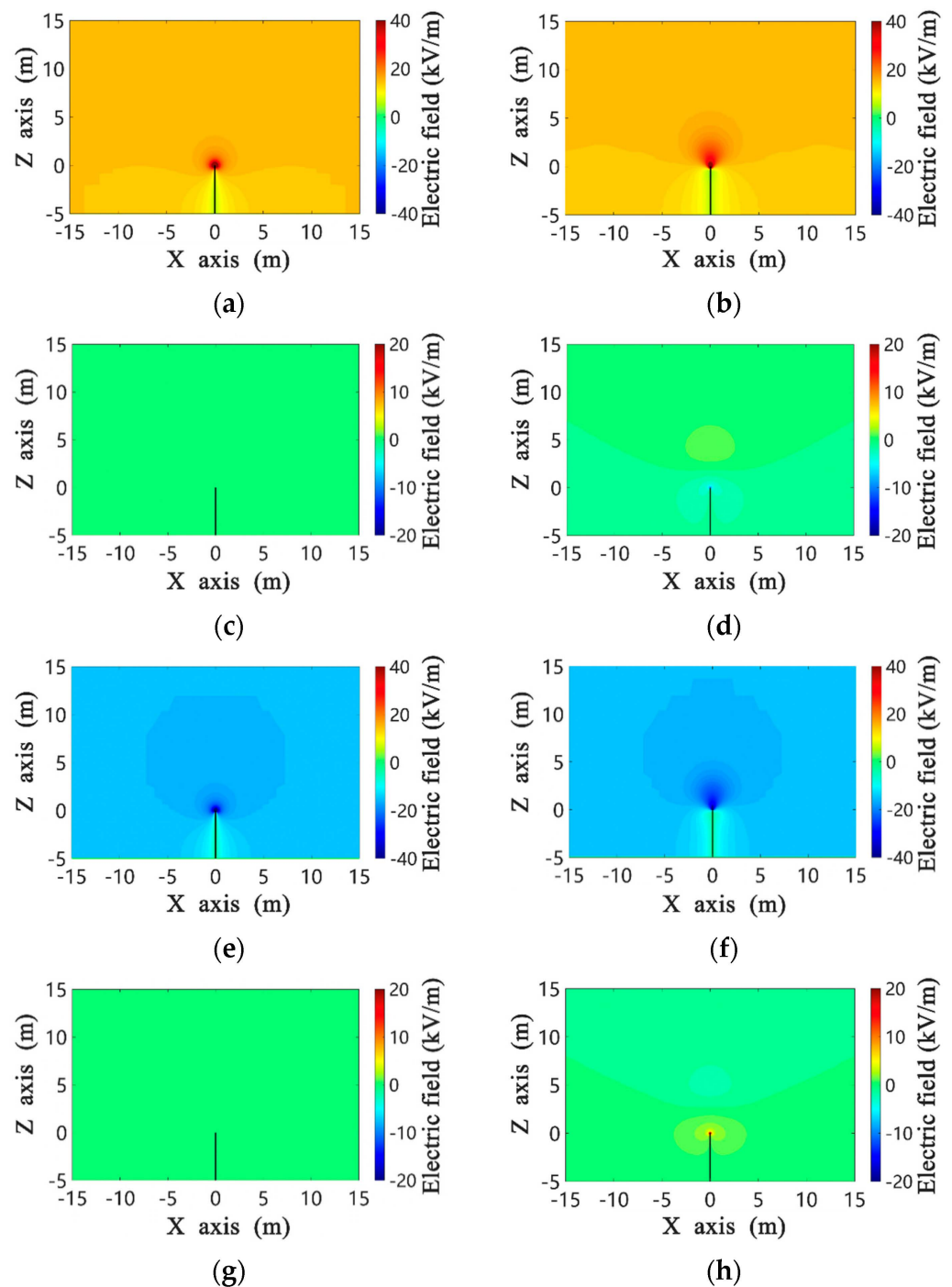


Figure 10. The spatial electric field distribution when the background electric field amplitude is 15 kV/m. (a) Positive peak time and no corona; (b) positive peak time with corona; (c) zero value moment and no corona; (d) zero value moment and corona; (e) negative peak time and no corona; (f) negative peak time and corona; (g) zero value moment and no corona; and (h) zero value moment and corona.

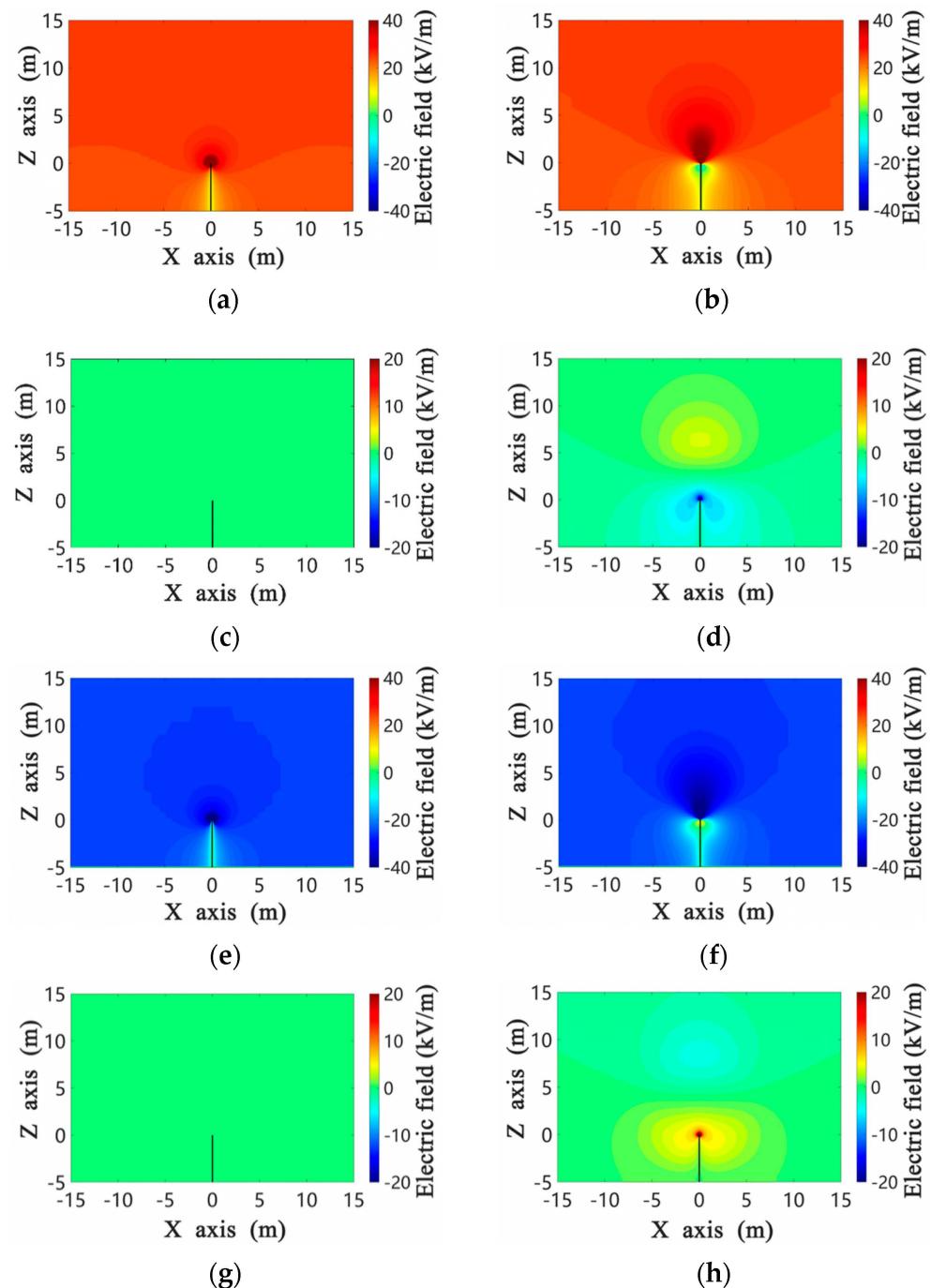


Figure 11. The spatial electric field distribution when the background electric field amplitude is 25 kV/m. (a) Positive peak time and no corona; (b) positive peak time with corona; (c) zero value mo-moment and no corona; (d) zero value moment and corona; (e) negative peak time and no corona; (f) negative peak time and corona; (g) zero value moment and no corona; and (h) zero value moment and corona.

The influence of different background electric field amplitudes on the near-surface atmospheric electric field also shows differences. For example, Figures 12 and 13 show the near-surface atmospheric electric field distribution map at each time point with or without corona.

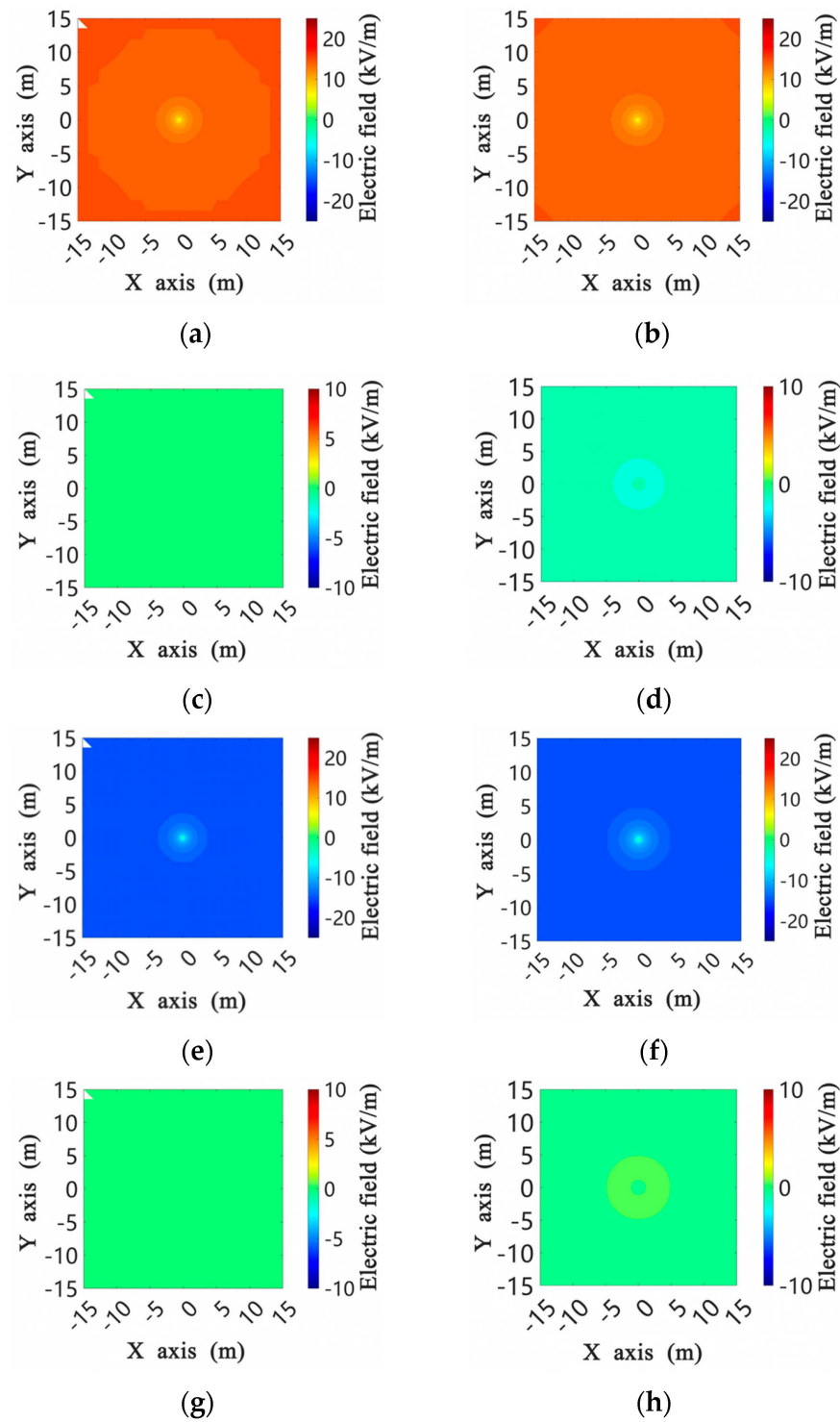


Figure 12. The distribution of the atmospheric electric field near the ground when the background electric field amplitude is 15 kV/m. (a) Positive peak time and no corona; (b) positive peak time with corona; (c) zero value moment and no corona; (d) zero value moment and corona; (e) negative peak time and no corona; (f) negative peak time and corona; (g) zero value moment and no corona; and (h) zero value moment and corona.

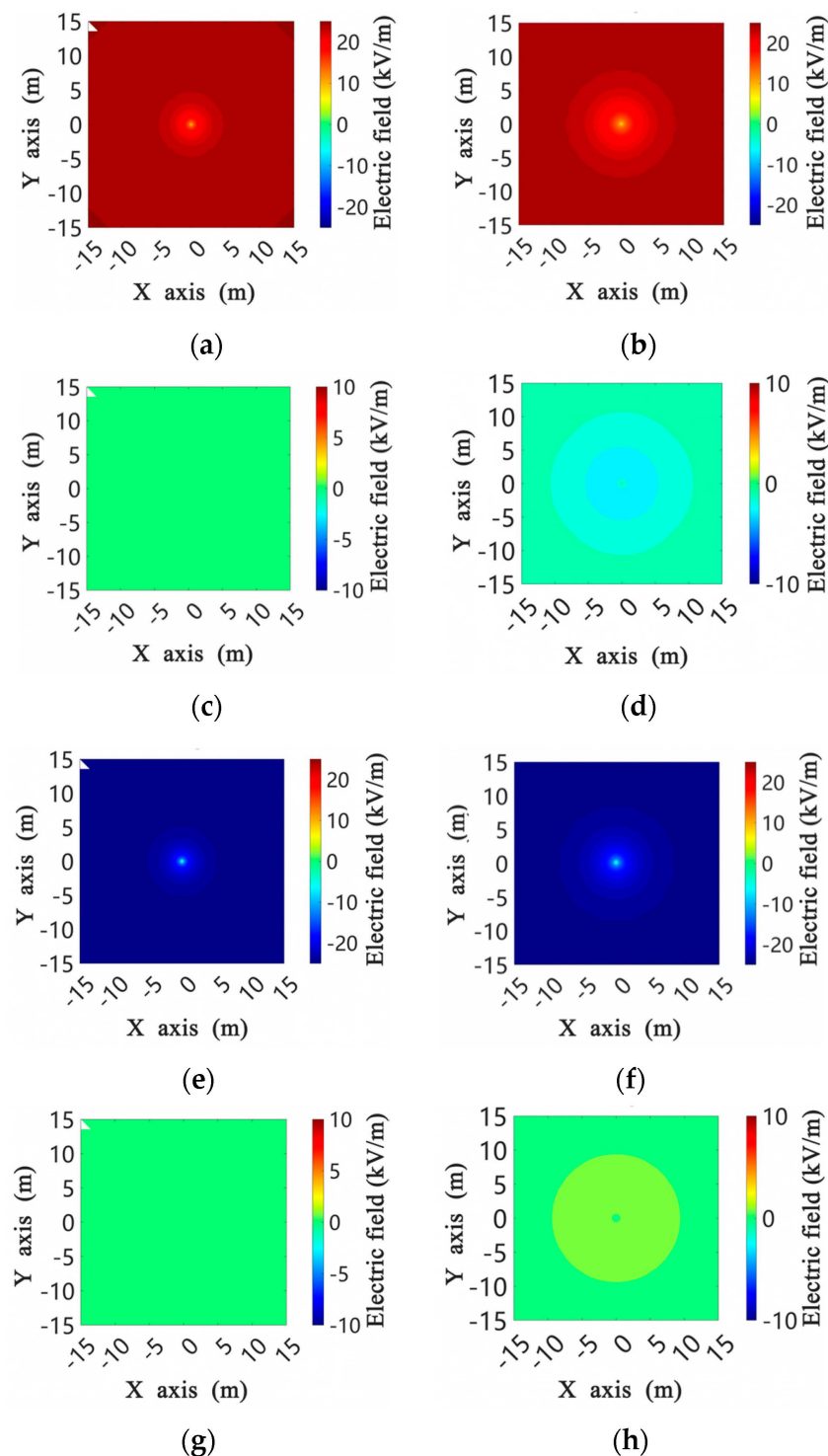


Figure 13. The distribution of the atmospheric electric field near the ground when the background electric field amplitude is 25 kV/m. (a) Positive peak time and no corona; (b) positive peak time with corona; (c) zero value moment and no corona; (d) zero value moment and corona; (e) negative peak time and no corona; (f) negative peak time and corona; (g) zero value moment and no corona; and (h) zero value moment and corona.

According to Figures 12 and 13, the distribution of the near-surface atmospheric electric field is consistent with the background electric field when there is no corona. When corona exists, the influence of the tip discharge on the near-surface electric field varies with the amplitude of the background electric field. With the increase in the background electric field amplitude, especially at the positive peak of the background electric field, the influence

of the tip corona discharge is obviously enhanced, and the influence on the near-surface atmospheric electric field is increased. When the background electric field has a negative peak, the effect of the tip corona discharge on the near-surface atmospheric electric field is significantly weaker than when the background electric field has a positive peak.

When the background electric field changes from positive and negative peaks to 0, the process of the background electric field falls from positive and negative peaks to zero, and the shielding effect of the corona discharge on the near-surface atmospheric electric field becomes more and more significant with the increase in field strength amplitude. When the background electric field rises from the negative peak to the zero value, the enhancement of the near-ground electric field by corona discharge also increases with the increase in field strength. Further analysis of the difference between the air and ground electric fields with or without corona discharge at the zero-crossing time of the electric field in Figures 10 and 11 shows that, due to the corona charge remaining in the air and slowly dissipating, its presence disturbs the amplitude and polarity evolution of the environmental background electric field. The specific behaviour is as follows: when the background electric field of a thunderstorm changes from positive polarity to negative polarity, if the corona effect is considered, the polarity reversal time of the ground electric field will appear in advance, and the higher the peak value of the background electric field strength, the greater the charge output and the greater the advanced amount; on the contrary, the reversal of the spatial electric field polarity above the corona layer shows a hysteresis characteristic, and the degree of hysteresis is also positively correlated with the peak background field strength. The above effects may pose potential interference to the method of monitoring thunderstorm dynamics based on the ground or air electric field data.

4. Conclusions and Discussion

In this study, a three-dimensional bipolar corona discharge model was used to numerically simulate the corona discharge behavior of an independent lightning rod with a height of 5 m under different amplitudes of positive and negative symmetrical triangular wave background electric fields. By investigating the regulation effect of electric field amplitude on the corona current, the total charge and the spatial electric field distribution, and comparing these with the results of the unipolar model, it is concluded that the background electric field amplitude plays a significant leading role in the intensity of the tip corona discharge. At the same time, the corona charge generated by the discharge will reverse modulate the environmental electric field distribution. When the thunderstorm background electric field undergoes polarity reversal, the corona charge accumulated before the reversal will significantly promote the discharge process after the reversal, and this promotion effect becomes stronger with the increase in the background electric field amplitude. The specific performance is as follows:

The peak value of the corona current is synchronized with the peak value of the background electric field and increases with the increase in the electric field amplitude. The peak value of the second half-cycle increases faster with the peak value of the background electric field. The specific relationship between the positive and negative corona current peaks is $I^+ = -3.335 + 0.890 E - 0.0336 E^2$, $I^- = -0.0532 - 0.153 E - 0.0682 E^2$, both of which reach the 0.05 significance level. Affected by the positive corona discharge in the first half-cycle, the negative corona current is advanced when the polarity of the electric field is reversed. The negative corona generation time at the electric field amplitude of 25 kV/m is 0.1647 s earlier than that at 5 kV/m, indicating that the positive corona charge accumulated in the positive half-cycle promotes the subsequent negative corona discharge with the increase in the background electric field amplitude.

The total corona charge peak in the air follows the quadratic function growth law with the increase in the background electric field peak in the first and second half-cycles. However, compared with the first half-cycle, the slope of the peak value of the second half-cycle is relatively flat alongside the increase in the field strength, and the final peak value is also lower than that of the first half-cycle due to the restriction of the heteropolar corona charge neutralization effect in the first half-cycle. The relationship between the total corona charge in the air of the first and second half-cycles and their respective peak values is as follows: $Q^+ = 2.43 \times 10^{-3} - 6.497 \times 10^{-4} E + 4.677 \times 10^{-5} E^2$, $Q^- = -3.18 \times 10^{-3} + 7.762 \times 10^{-4} E - 4.671 \times 10^{-5} E^2$, both of which reached a significant level of 0.05. It shows that the heteropolar charge accumulated in the first half-cycle has an inhibitory effect on the charge accumulation in the second half-cycle, and this effect changes significantly with the amplitude of the electric field.

The influence of the tip corona discharge on the near-surface atmospheric electric field increases with the increase in the background electric field amplitude. The effect is most significant at the positive peak and is relatively weak at the negative peak. When the background electric field changes from peak to zero, the shielding effect of the corona discharge on the near-ground electric field increases with the increase in amplitude. When the electric field crosses zero, the corona charge leads to a significant difference in the electric field with and without corona and affects the polarity and change in the environmental electric field. In the process of a thunderstorm, the background electric field changes from positive to negative, the corona effect makes the polarity reversal time of the ground electric field advance, and the larger the amplitude is, the larger the advance is. The reversal time of the electric field over the corona layer lags behind, and the lag increases with the increase in the amplitude.

It can be seen from this study that the characteristics of the thunderstorm background electric field play a key role in the evolution of the ground-tip corona discharge. Specifically, the electric field amplitude determines the overall strength of the discharge; under the polarity reversal condition, the charge released in the first half-cycle will have a significant promoting effect on the discharge in the second half-cycle, which is also worthy of attention. In the future, we will further introduce asymmetric waveforms, measured thunderstorm waveforms, and complex multi-tip structures to more fully reveal the characteristics of the ground-tip corona discharges in thunderstorm environments and the mechanism of their impact on the ambient electric field, providing theoretical and technical support for lightning monitoring and early warning systems.

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