Corona Charge Produced By Thundercloud Fields In Grounded Rods

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Abstract—Electrostatic fields below the thundercloud lead to the formation of glow charge from grounded objects. The charge accumulated after certain time can initiate or inhibit the called streamer formation and consequently the inception and development of upward leaders. By means of a two dimensional numerical model that takes into account the particles behavior is observed that glow charge can smooth the electric field on top of the grounded rod and consequently hinder the inception of streamers and upward leaders from the grounded rod. It is concluded that to be able to initiate unstable upward leaders from the shielded grounded rod a sudden change of electric field is necessary.

A two dimensional numerical model that solves the continuity equations for positive and negative ions and electrons coupled with Poisson equation was implemented. Comparison for different magnitudes of electric field and characteristics of rod are included as well.

Keywords—glow charge; streamer; inception; electric field

I. INTRODUCTION

During thunderstorms, the electric field beneath thunderclouds can initiate the glow corona at grounded objects. The corona space charge will locate at the tip of grounded structure. The space charge above the rod will produce a redistribution of the electric field near the rod tip. The presence of the space charge will change the development of unstable upward connecting leaders from grounded objects and therefore it might change the conditions required to get a lightning strike.

Several investigations [1-9] have shown that a glow corona initiated from the top of a grounded object strongly affects the initiation and development of an upward leader from it. Consequently, prior to analyze the leader initiation and progression, it is necessary to understand the characteristics of the non-stationary corona occurring near the tip of a rod in the atmospheric electric field.

The purpose of this work is to analyze the main aspects of the electrical charge initiated from grounded objects during thunderstorm electric fields. To understand those discharges at standard temperature and pressure, a numerical model was implemented. The model used microscopic mechanisms in air and included processes such as photoionization, background ionization, electron impact excitation and ionization, thermal and nonthermal attachment and detachment processes, etc.

The paper is limited to the case of positive corona discharge and negative cloud-to-ground lightning and it is dedicated to the initial phase of the discharge before the development of an upward connecting leader.

II. MODELING

In this study, a quasi two-dimensional model of the corona discharge was used. To model the principal behavior of the corona, only one generic positive ion species and one generic negative ion species were included. Hence, the detailed chemical kinetics of the discharge plasma was not considered. Ionic diffusion was not taken into account. Under these conditions, the system of continuity equations for densities of electrons, positive and negative ions was written in the following manner:

\[
\frac{\partial N_e}{\partial t} = \sum_{i} \alpha_i W_i \left[ -N_e N_i \beta - \frac{\partial (N_e W_e)}{\partial x} \right] 
\]

\[
\frac{\partial N_p}{\partial t} = \sum_{i} \alpha_i W_i \left[ -N_p N_i \beta - \frac{\partial (N_p W_p)}{\partial x} \right] 
\]

\[
\frac{\partial N_n}{\partial t} = N_p e \left[ -N_e N_p \beta - \frac{\partial (N_n W_n)}{\partial x} \right] 
\]

\[
\frac{\partial N_m^i}{\partial t} = \delta_i W_m N_e e - \frac{N_m^i}{\tau_m^i} 
\]

\[
\frac{\partial N_p^i (r, \theta, \phi, t)}{\partial t} = \frac{N_p^i (r, \theta, \phi, t)}{4 \pi \tau_i^m} - \mu_i C_i N_p^i (r, \theta, \phi, t) - \sigma_i N_p^i (r, \theta, \phi, t) 
\]

Where \( t \) is the distance from the anode; \( N_e, N_p, N_n \) and \( N_m \) are the respective electron, positive ion, negative ion and molecule densities; and \( W_e, W_p, W_n \) the respective electron, positive ion and negative ion drift velocities. The superscript \( i \) denotes the \( i^{th} \) excitation coefficient of a molecule level and also photons emitted from that level. \( \delta_i \) is the excitation coefficient level, \( \mu_i \) and \( \tau_{mi} \) are the respective
photon absorption coefficient and the excited molecule lifetime from that level. \( N_{ph}(r, \theta, \phi, t) \) is the photon density at \( r \) in real space per steradian in the direction of velocity in polar coordinates \((\theta, \phi)\). The symbols \( \alpha, \eta \) and \( \beta \) denote the ionization, attachment and recombination, \( c \) is the speed of light, \( \varsigma \) the photon velocity and \( S \) is the source term due to photoionization.

All coefficients in the system of equations (1) to (5) are functions of the local electric field strength. When the local electrical field is modified by space charge, the coefficients in the above equations become space and time dependent. The magnitudes of the rate coefficients and their dependences on the electric field were taken from Morrow [9-10]. In the present work, the photoionization rate is assumed proportional to the electron ionization rate [11-12]. The model solves Poisson’s equation simultaneously with the continuity equations.

\[
\nabla^2 \phi = -\frac{1}{\epsilon} \left( \frac{N_e - N_p - N_0}{e} \right)
\]

(6)

where \( \epsilon \) is the dielectric constant, \( e \) the electron charge and \( \phi \) the electric potential.

A. Boundary and initial conditions

The boundary conditions for the equation system are the following: At absorbing boundaries, the particles densities are finite and are determined by the flux from the discharge body. [9 - 10, 13]

All the continuity equations require a boundary condition according with equation degree of derivation. The continuity equation for electrons is a second order equation and therefore it requires two boundary conditions: At \( z = 5000 \), \( N_e = 0 \); and at \( z \) near to the tip of the rod an initial Gaussian electron density was considered \( 10^4 \text{ cm}^{-3} \), which represents the available electrons at the gap. The photoionization process is included as secondary emission effect. Continuity equations for positive and negative ions are both first order equations and thus require only one boundary condition each: at the cathode \( N_p = 0 \); and at the anode \( N_e = 0 \).

The system of equations was solved by the flux corrected transport (FCT) technique with Zalesak’s peak preserver routine modifications, as described in detail by Kennedy [14 - 15].

An hyperboloid coordinate system with axial symmetry \((r, z)\) is used to simulate the space charge around a \( l \) m height grounded rod with different hemispherical tip radius, located on flat area.

The analysis domain is defined from the ground \( Z_0 \) to the cloud center \( Z_f \) (taken as 5000 m). The background electric field produced by the cloud itself started from time \( 0 \) s to \( t_f \) by increasing from 0 to a maximum that will vary between 1 to 100 kV/m and then the electric field is kept constant. The time \( t_f \) is changed from 10 to 30 s, which corresponds to the time of formation of charged regions inside clouds as it has been found by [16].

III. RESULTS AND DISCUSSION

Simulations for different lengths of the rod, tip radius, maximum electric field and \( t_f \) were performed. The most relevant results are presented and analyzed here.

A. Charge density distribution

The spatial location of the glow corona charge in coordinates \( r \) and \( z \) under different thundercloud electric fields was compared. Fig. 1 shows the distribution of charge for a rod of 20 m height exposed to a background electric field variable from 0 to 16 kV/m during \( t_f \) of 10s and after 30 s of a constant electric field of 16 kV/m. The different colors represent the charge density (particles / m\(^3\)).

![Figure 1. Charge distribution of a rod of 20 m height after application of variable electric field. The colors indicate the density of particles. Notice that the figure corresponds to a case of radial symmetry.](image)

The results showed that for the same lightning rod under different background electric fields, the distribution of the charge in \( r \) and \( z \) varies. A sample of the obtained results is presented in Fig. 2.

All performed simulations indicate that the spatial location of the charge for different thunder electric fields and the same lightning rod has the following characteristics:

1. The higher the electric field, the longer the \( z \) distance covered by the charge.
2. The radii covered by the charge changes with the increment of electric field.
3. Once the electric field is constant the ionic charge keeps approximately the same location at \( r \) and \( z \) axis.
The charge produced by thundercloud electric fields after several seconds reaches a maximum radius and axial distance from the tip of the rod. The maximum distance reached by the charge depends on the magnitude of the electric field.

B. Current Characteristics

The calculations of the glow current for the different cases have shown that the current increases with a constant rate when the electric field rises linearly. At constant $E_0$ the current decreases with a lower rate (see Fig. 3). The constancy or low rate of decrease of the current at constant $E_0$ is more pronounced for higher electric fields than for lower electric field magnitudes. The effect of change of the electric field on the temporal evolution of the current is associated with the expansion of the corona space charge cloud from the electrode; the distance covered by the space charge front increases noticeably under higher electric fields.

The current does not reduce to zero after 60 s under constant electric field. This behavior can be explained because the positive and negative ions located near to the tip of the rod and their slow velocity of propagation (see Fig. 4). However, one should keep in mind that processes as diffusion and weather changes as wind and rain [3 - 4] are not considered in this model.

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1) Variation of current with change of time $t_1$

Calculations showed that the maximum current reached depends on the time $t_1$ the lightning rod is exposed to an increasing $E_0$. It is observed that the current rises linearly in time at a linear increase in $E_0$ and decreases slowly at $E_0 =$ constant. Comparing Fig. 3 and Fig. 5 can be seen that the current reaches higher values if the grounded object has a larger height.

2) Variations due to the geometrical changes of the rod

Results have shown that other parameter involved on the accumulation of charge is the size of the tip of the rod. Fig. 6 summarizes the results for different radii of the tip of the rod. One can observe that the smaller the radius of the tip of the rod, the higher the charge accumulated. However, notice that after
12 s the current decreases and it reaches roughly the same current magnitude.

Figure 6. Current vs time for different rod tip radii. The results are for a rod 10 m length, 10 kV/m electric field and t1 1 s. The smaller the radius of the tip of the rod, the higher the current.

C. Inception of streamers and/or unstable upward connecting leaders

1) Streamer inception criterion evaluation

There are three conditions that should be met to obtain streamer inception: A free electron, an applied field above the critical field strength $E_{cr}$, and a critical distance $d_{cr}$. If one or more of these conditions is only marginally met then the streamer might or might not start. Considering that the background electric field has been modified due to the presence of space charge, the streamer criteria is evaluated [18]:

$$\exp \left[ \int_{\Delta x} (\alpha - \eta) \cdot dx \right] \geq N_{stab} \quad (6)$$

where $\alpha$ is the first ionization coefficient, $\eta$ is the attachment coefficient and $\Delta x$ is the size of the active region where $(\alpha - \eta) > 0$ and $N_{stab}$ is the minimum charge that produces a space charge field high enough to reproduce the streamer tip. The ionization and attachment coefficient are calculated as function of the local fields. The stability charge depends on the applied electric field.

Table I presents the results obtained for a rod of 60 m length while the electric field is increased from 5 kV/m at 10 s and with the same rise time until 20 kV/m. The results indicate that even though the electric field is increased, the effect of the glow charge and the low rate of increment of electric field do not allow the inception of streamers from the rod.

<table>
<thead>
<tr>
<th>Maximum electric field [kV/m]</th>
<th>Streamer inception</th>
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<tbody>
<tr>
<td>5</td>
<td>YES</td>
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<tr>
<td>6</td>
<td>YES</td>
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The streamer criterion evaluation, the current calculation and charge distribution analysis indicates that for thundercloud electric fields higher than 10kV/m a glow corona charge cloud will locate on the tip of the lightning rod. The charge will shield the lightning rod and the electric field will be distorted. The glow charge will smooth the electric field on top of the rod to the point that streamers can not be initiated.

Once the rod is shielded, the conditions to incept an upward leader from the grounded rod will be different than the case without the glow corona charge:

1. The constant electric field prevents the electric field in the gap from increasing above and keeps the ionization layer from expanding into the gap.
2. The spatial distribution of potential near the grounded electrode becomes smoother than in the absence of the glow corona.

To surpass the effect of the glow corona a sufficiently high electric field should be reached or an abrupt change of the background electric field will be necessary to neutralize the charge and to incept an upward leader from the grounded rod.

Therefore, the following hypothesis is proposed: “As the rod is shielded by the corona charge, the only possibility to incept an upward leader from the grounded rod is that a sudden change of electric field neutralizes the charge and incepts an upward connecting leader from the grounded object”.

To verify the hypothesis the background electric field has risen linearly from zero to a magnitude were without space charge inception of streamers and unstable leaders could be incepted. The electric field is raised slowly. The streamer inception and leader inception criteria are evaluated at each instant of time. If non streamer or leaders are incepted, the electric field will continue increasing at the same rate until it reaches a magnitude equivalent to twice the electric field required for inception without space charge. Finally, if not inception is observed the electric field is dropped to a magnitude closer to the magnitude where inception of streamers without space charge is obtained. This sudden reduction of electric field could represent a lightning flash from the cloud to a different point far from the lightning rod under study.

In the model, the corona inception is evaluated using the well-know streamer inception criterion while the transition from streamer to leader is assumed to take place if the total charge in the second or successive corona bursts is equal to or larger than about 1µC [18].
In this paper the described method is applied to one particular case, the arrangement of a rod of 100 m length and tip radius of 0.01 m. For the rod of 100 m height without space charge, streamer inception and unstable leader criteria are calculated. Inception of streamers and upward leader inception are obtained at 25 kV/m. Consequently, the thundercloud electric field assumed was zero at \( t = 0 \) and rose linearly to 25 kV/m at 20 s. The electric field continues rising to 50 kV/m, streamer and leader criteria are evaluated. Then suddenly the thunder electric field falls to 25 kV/m.

Figure 7 illustrates the magnitude of the charge during the rising of electric field. Before the dropping of electric field at 40 s the total accumulated glow charge on top of the rod is of 0.78 mC. At this instant the streamer criterion was evaluated and was not fulfilled.

As the electric field on top of the grounded electrode has been smoothed due to the space charge, the streamers can not be incepted from the shielded rod. This effect is illustrated in Fig. 8, which shows the calculated distribution of the electric field near the rod tip. This distribution is compared with the electric field distribution in the absence of space charge. The effect of space charge is most deep within the first centimeters. Consequently, the streamer criterion is not fulfilled.

Once the electric field is reduced to 25 kV/m, it is assumed that the total charge of the glow corona charge was completely removed from the tip of the rod. The streamer criterion is evaluated and streamers are incepted from the rod due to the thundercloud electric field. No more details regarding the propagation or stabilization of the leader channel can be given at this stage, ongoing work of the authors is related with the evaluation of the connecting upward leaders and results will be available in the future.

**IV. CONCLUSIONS**

The results of the present paper under the assumptions of the model indicate that during the charging process of the thunderclouds a glow corona layer could be formed on top of grounded lightning rods. The effect of the slow change of the background electric field is to shield the grounded rod. The formed glow charge will smooth the electric field on top of the grounded rod and will inhibit the generation of streamers and it will hamper the inception of upward leaders.

It was demonstrated as well that a sudden change of electric field could neutralize the glow charge and if the electric field changes fast the inception of unstable upward leaders from the grounded rod could be observed. These unstable leaders could end in connecting upward leaders.

Results have shown that the generation and particles density at top of the grounded rod depend on the magnitude of the background electric field and the geometrical characteristics of the grounded rod.

**REFERENCES**