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Drift of Space Charge Produced by Glow Corona during Thunderstorms

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Abstract: Glow corona discharges are generated from tall objects during thunderstorms previous to a lightning strike. In order to quantify the shielding effect of these discharges, a transient, two dimensional model of the drift of the space charge generated on the tip of tall objects under the thundercloud electric field is performed with COMSOL Multiphysics. The simulation allows estimating the spatial distribution of the space charge generated by glow corona, as well as the evaluation of its shielding effect on the initiation of subsequent streamer discharges. It is found that the shielding potential of the corona space charge is not as severe as reported in previous studies based on a simplified approach.

Keywords: Glow corona, Lightning, Ion transport, electrostatic shielding.

1. Introduction

Glow corona discharges are readily initiated from the tip of tall slender grounded objects due to the electric field created by thunderclouds. When the polarity of the thundercloud is negative, these discharges generate positive ions which start moving upwards under the influence of the background electric field. If the generation of space charge is sufficient, these ions can shield and hinder the development of subsequent discharges (e.g. streamers and leaders) prior to a lightning strike.

The existing theoretical analyses of the drift of glow corona space charge have been performed in one dimension [1, 2]. Such studies assume that the ions generated at the tip of a grounded object expand radially, holding a semi-hemispherical shape as they drift into the gap (Figure 1). Under this assumption, the modelling of the ion drift is simplified to a single dimension. The results of these studies suggested that the glow corona can delay the inception of streamers and therefore, it later can inhibit the initiation and propagation of upward leader discharges. Thus, it was proposed that glow corona could be used to control lightning strikes to grounded objects.

However, this proposal has been widely debated among practical engineers and scientists since it has been used to support the usage of unconventional lightning protection systems [3]. In order to contribute to the scientific discussion on this issue, a two-dimensional analysis of the corona space charge drift is performed with COMSOL Multiphysics 3.5. Thus, this paper introduces to the implementation of such model and the preliminary results obtained.

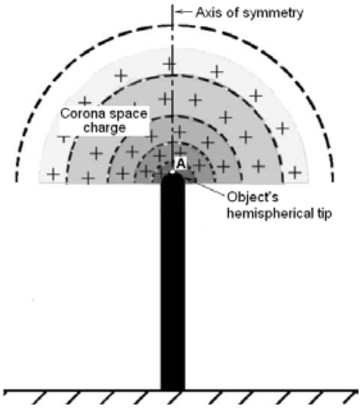

Figure 1. Sketch of the semi-hemispherical expansion of the corona space charge according to the 1D approximation (adapted from [1]).

2. Governing equations

In order to properly evaluate the drift of corona ions from lightning rods, the one dimensional model proposed by Aleksandrov *et al* [1-2] is extended to two dimensions. For this, three convection/diffusion modules and an AC/DC module of COMSOL Multiphysics are used to solve the continuity equations for small ions n_+, large aerosol ions N_+ and aerosol neutrals N_a:

$$\frac{\partial n_+}{\partial t} = D \cdot \nabla^2 n_+ - \nabla \bullet \left(n_+ \cdot \mu_{n+} \cdot \overline{E} \right) - k_{nN} \cdot n_+ \cdot N_a$$

$$\frac{\partial N_+}{\partial t} = D \cdot \nabla^2 N_+ - \nabla \bullet \left(N_+ \cdot \mu_{N+} \cdot \overline{E} \right) + k_{nN} \cdot n_+ \cdot N_a$$

$$\frac{\partial N_a}{\partial t} = D \cdot \nabla^2 N_a - k_{nN} \cdot n_+ \cdot N_a$$

together with the Poisson's equation for electric field $\overline{E}$ and potential Φ:

$$\nabla\cdot\bar{E} = -\nabla^2\Phi = \frac{e\cdot\left(n_+ + N_+\right)}{\varepsilon_0}$$

where μ_{n+} and μ_{N+} are the ionic mobilities for small and aerosol ions respectively. k_{nN} is the small positive ion attachment coefficient to aerosol particles, D is the diffusion coefficient, e is the elementary charge and ε_0 is the dielectric permittivity.

In the absence of wind, the space charge emission from a lightning rod has axial symmetry. Therefore the problem is reduced to a 2 dimensional, axial-symmetric coordinate system to properly represent the electric field produced by the rod and the drifting space charge. Thus, the previous continuity equations are rewritten according to the generic form of the convection/diffusion equation in COMSOL Multiphysics [2] as:

$$\frac{\partial n_+}{\partial t} + \nabla(-D\nabla n_+) = \left(-n_+\cdot\mu_{n+}\cdot\frac{e\cdot\left(n_+ + N_+\right)}{\varepsilon_0} - k_{nN}\cdot n_+\cdot N_a\right) - (\mu_{n+}\cdot\bar{E})\bullet\nabla n_+$$

$$\frac{\partial N_+}{\partial t} + \nabla(-D\nabla N_+) = \left(-N_+\cdot\mu_{N+}\cdot\frac{e\cdot\left(n_+ + N_+\right)}{\varepsilon_0} + k_{nN}\cdot n_+\cdot N_a\right) - (\mu_{N+}\cdot\bar{E})\bullet\nabla N_+$$

$$\frac{\partial N_a}{\partial t} + \nabla(-D\nabla N_a) = \left(-k_{nN}\cdot n_+\cdot N_a\right)$$

The mobilities are taken as μ_{n+}=1.5·10^{-4} m^2 s^{-1} V^{-1} for small positive ions and μ_{N+} =1.5·10^{-6} m^2 s^{-1} V^{-1} for large positive ions. The rate of conversion of small ions into aerosols k_{nN} is assumed to be equal to 2.9·10^{-12} m^3 s^{-1}, while the diffusion coefficient D is chosen as 1 m^2 s^{-1}. The values used for these quantities are taken from [3]. ε_0 is the dielectric permittivity of vacuum and e is the elementary charge.

For the model, a subdomain *A* is used to describe the region where space charge drifts within the simulation time window, while the rest of the geometry is covered by a second subdomain *B*. To reduce the number of mesh points and maintain the accuracy of the calculations, different meshing is used for the subdomains. The subdomain *A* has a mapped mesh distributed exponentially along the longitudinal edges. Linear mapping uniformly distributed is used for the transversal edges of this subdomain. Free meshing of normal predefined size is used for the subdomain *B*.

The boundary conditions used in the models are as follows. For the electrostatics module, a time varying potential with voltage V_{plane} =E_{back} ·H is applied to the upper plane boundary, where E_{back} is the background electric field and H is the height of the plane. The left vertical boundary is set as the axis of symmetry while the right vertical boundary is defined as an electric insulation. The other boundaries are set as zero potential.

For the convection/diffusion module, the upper horizontal boundary is set as a convection edge and the remaining boundaries (except the rod surface boundary) are considered as a zero flux boundaries. The surface of the rod where the local electric field is equal to or larger than the onset corona field E_{cor} is defined as a concentration boundary. Since the thickness of the ionization layer is neglected, the corona ions are assumed to be emitted from the rod's boundary that satisfies this condition. In such case, the concentration (density) of small ions at this boundary $n_+^{(rod)}$ is defined such that the electric field on the surface E_{rod} remains constant and equal to E_{cor} (i.e. the Kaptzov's assumption). Therefore an extra global equation, the unknown constrain $n_+^{(rod)}$, is added to the system such that the equation:

$$E_{rod}(t) - E_{cor} = 0$$

is satisfied. The corona onset electric field E_{cor} is estimated with the well-known Peek equation. Due to the time variation of the background electric field in the simulations presented in the following sections, the area of the corona-emitting surface of the rod is updated periodically to maintain its electric field within the range E_{cor}±5%. The initial concentration of small ions is assumed to be zero. Transient analysis with the direct UMFPACK iterative solver is used for the multiphysics model.

3. Results

A single study case of a 60 m tall rod with 0.02 m cap radius is presented in the paper. Figure 6 shows an example of the corona space charge spatial distribution during the thundercloud charging process. The thundercloud electric field is assumed to increase linearly up to 20 kV/m in 10 s. From this figure, several differences are found compared with the 1D approximation considered by the previous studies. First, there is a significant amount of ions that diffuse downward into areas with relatively low electric field beside the rod's body (Figure 2). Second, the effective generation of glow corona does not take place all over the surface of the rod's cap. For the analysed case, corona can only be produced on 55% of the upper surface of the rod's cap since the electric field on the remaining part of the rod cap is lower than the corona inception field. Consequently, the effective corona generating surface on the rod cup is considerably smaller than that assumed by the 1D approximation. Third, the corona space charge does not naturally propagate in the radial direction as much as assumed by the 1D approximation. This reflects in the fact that the total amount of space charge injected in the gap is overestimated by the 1D approximation. In this case, the computed total corona charge computed with the 1D approximation is 1.2 mC, which is 40% larger than the 0.85 mC computed with the 2D model here presented.

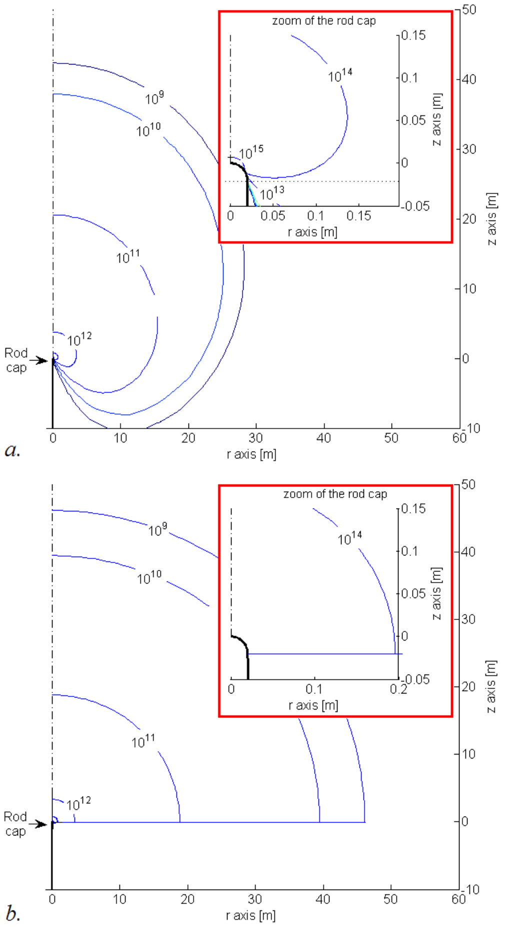

Figure 2. Contour plot of the small ion density per cubic meter produced by corona from a 60 m tall rod after the thundercloud electric field has reached 20 kV/m with *a*) the 2D model and *b*) the 1D approximation. The lower part of the rod is not shown.

Another interesting condition to consider when evaluating the corona ion drift is under the presence of the electric field generated by a descending lightning stepped leader. For this, the descending stepped leader channel is represented by a non-uniform vertical line charge along the axis of symmetry. The downward leader charge distribution proposed by Cooray et al [4] is used as a function of both the prospective return stroke current peak (taken as 30 kA) and the height of the downward leader tip above ground z_{down}. The stepped leader is assumed to start propagating from the cloud base (z_{down} = 4000 m) towards the ground with an average velocity 2 x 10^5 m/s. The initial condition for the corona calculation is taken from the previous stage when the thundercloud electric field reaches 20 kV/m.

Due to the short duration of this stage, the generated corona ions cannot drift far from the rod tip during the fast approach of a stepped leader, as it can be seen in Figure 3. For instance, the small ion density along the axis of symmetry only changes significantly within 0.2 m from the rod tip when z_{down} = 1640 m compared with the initial distribution (z_{down} = 4000 m). About two milliseconds later when the downward leader tip is about 530 m, the produced corona ions drift further into the gap although they do not advance more than 0.6 m from the rod tip. However, the small ion density at the rod surface (at z = 0) reaches values one order of magnitude larger than for the reference distribution. Consequently, considerable amounts of space charge are built up in the close proximity of the rod tip as the downward leader approaches to ground. This charge accumulation strongly shields the spatial electric field distribution in front of the rod tip, as reported in [1, 2].

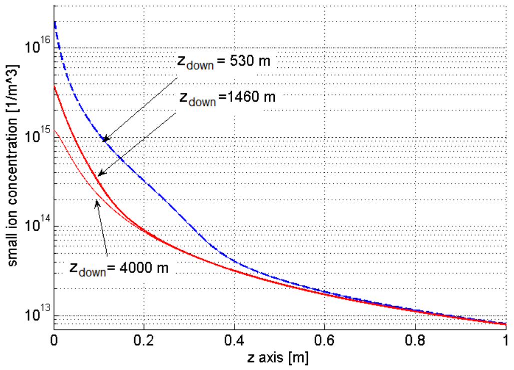

Figure 3. Small ion concentration computed along the axis of symmetry at the start of the downward leader propagation and when the downward leader tip reaches 1460 m and 530 m above ground.

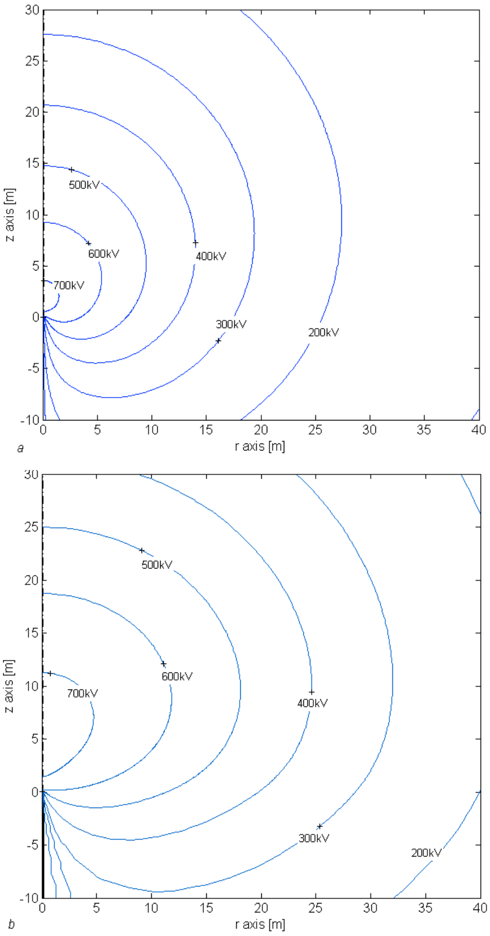

Figure 4. Contour plot of the shielding potential of the generated space charge produced by corona from a 60 m tall rod computed with *a*) the 2D model and *b*) the 1D approximation. The figures correspond to the results when the downward leader tip is 1200 m above ground.

Since the shielding effect of the generated space charge can influence subsequent discharges, it is of interest to estimate its shielding potential. An example of the differences on the potential of the space charge (alone) computed with the here introduced 2D model and with the 1D approximation is shown in Figure 4. In this case, the downward leader tip z_{down} is located 1200 m above ground. Although the peak shielding potential in both cases reach a similar value (around 700 kV), the 1D approximation generally overestimates the areas with significant shielding (Figure 4.b) compared with the 2D simulation (Figure 4.a). Particularly, the 1D approximation miscalculates the potential in the radial direction. For instance, observe that maximum shielding potential estimated with the 1D approximation at a radial distance of 25 m is about 400 kV. This value is almost double of the shielding potential computed with the 2D model (of about 200 kV).

7. Conclusions

A 2 dimensional COMSOL Multiphysics model of the drift of ions generated by glow corona at the tip of sharp objects under thunderstorms has been introduced. The analysis avoids several assumptions considered in previous studies reported in the literature [1–3]. The obtained results shows clear differences between the estimations of the 2D model and the results based on the 1D approximation assumed in [1–3]. It is shown that the effective shielding effect of the space charge generated by glow corona is significantly lower than that reported in previous studies.

8. References

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