

ON THE TRANSITION FROM POSITIVE GLOW CORONA TO STREAMERS IN AIR

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ABSTRACT

The transition phase from glow to streamer corona is of significant importance for the evaluation of leader discharges initiated from ultra-high voltage power transmission lines under thunderstorms. In order to study the condition required for streamer inception from a glow-corona generating wire, the continuity equations for electrons, positive ions and negative ions coupled with Poisson's equation are solved. The calculations are performed for a wire-cylinder coaxial configuration in one dimension. The analysis is performed by considering the generation of glow corona under a DC electric field, followed by the transition to a streamer-like ionization wave under a fast-changing electric field ramp. Thus, the critical rate of rise of the applied voltage on the wire surface required for streamer-like structures to initiate in the presence of a stable glow corona is evaluated for different radii and DC voltages.

1. INTRODUCTION

The positive corona discharge in air at atmospheric pressure occurs in two distinct forms: the streamer discharge and the glow discharge [1]. The transition phase from glow to streamer corona is of significant importance for the evaluation of the initiation of leader discharges from ultra-high voltage power transmission lines under thunderstorms [2, 3]. However, no direct experimental results about the transition phase under those conditions are found in the literature.

In 1997, Morrow conducted a series of numerical simulations in one dimension for the concentric spheres or concentric cylinders electrode

arrangements. It was shown that the streamer-like ionizing waves from a 2 cm inner sphere occurred if the voltage was raised at a rate larger than 1 kV/ μ s in the presence of stable glow corona [4]. However, it is difficult to extrapolate this result to the actual case of glow to streamer transition from power transmission lines since the gap between the inner and outer spheres in the simulation was only 2 cm.

In the present paper, a similar analysis as in Morrow's [4] is performed to obtain characteristics of corona discharge with larger air gaps. For this, the continuity equations for electrons, positive ions and negative ions coupled with Poisson's equation are solved. The analysis is performed by considering the generation of glow corona under DC electric field, followed by the transition to streamers under fast-changing electric fields. The critical rate of rise of the applied voltage for the transition from positive glow corona to streamers is evaluated by a series of simulations. The surface electric field is also discussed both during a constant and a fast-changing electric field.

2. NUMERICAL MODEL

The hydrodynamic fluid model for corona discharge contains the continuity equations for electrons, positive ions and negative ions coupled with Poisson's equation. For a cylindrical coordinate system the equations are

$$\frac{\partial N_e}{\partial t} = S(r) + (\alpha - \eta) N_e |W_e| - N_e N_p \beta + k_d O_2^* O_2^- \quad (1)$$

$$-\frac{1}{r} \frac{\partial(r N_e W_e)}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} \left(r D \frac{\partial N_e}{\partial r} \right) \\ \frac{\partial N_p}{\partial t} = S(r) + \alpha N_e |W_e| - N_e N_p \beta - O_2^- N_p \beta - \frac{1}{r} \frac{\partial(r N_p W_p)}{\partial r} \quad (2)$$

$$\frac{\partial O_2^-}{\partial t} = \eta N_e |W_e| - k_d O_2^+ O_2^- - O_2^- N_p \beta - \frac{1}{r} \frac{\partial(r O_2^- W_n)}{\partial r} \quad (3)$$

$$\frac{\partial O_2^+}{\partial t} = N_e \alpha_m |W_e| - k_d O_2^+ O_2^- - k_q O_2^+ O_2 \quad (4)$$

where t is the time and r is the radial position. N_e , N_p , O_2^- and O_2^+ are the number densities of electrons, negative oxygen ions and metastable ($^1a\Delta_g$) oxygen molecules, respectively. W_e , W_p and W_n are the drift velocities for electrons, positive ions and negative ions and D is the electron diffusion coefficient. The gas medium is air at atmospheric pressure and the symbols α , η , β denote the ionization, attachment, electron-ion recombination coefficients, respectively. The term S is the source term due to photo-ionization. Poisson's equation is given by

$$\nabla \cdot (\epsilon_r \nabla \varphi) + \frac{e}{\epsilon_0} (N_p - N_n - N_e) = 0 \quad (5)$$

where ϵ_0 is the dielectric constant of free space, ϵ_r the relative permittivity, e the electron charge and φ the electric potential. In order to solve accurately the continuity equations for configurations with large gaps, the fixed moving particle method (FMPM) [5] is here used. Since it belongs to a Lagrangian scheme, it is significantly faster and more efficient than the widely used flux corrected transport method. Moreover, it is very suitable for handling non-uniform meshes and boundary conditions.

Figure 1 illustrates an example of the simulated corona current and density distribution of the considered particles for a concentric cylindrical configuration with inner and outer radius of 0.1 cm and 2.1 cm respectively. Observe that the simulated current amplitude (ranging between 10 to 30 mA/m) and current pulse period (of about 3 μ s) when 30 kV are applied to the configuration is in good agreement with the estimates reported in [4].

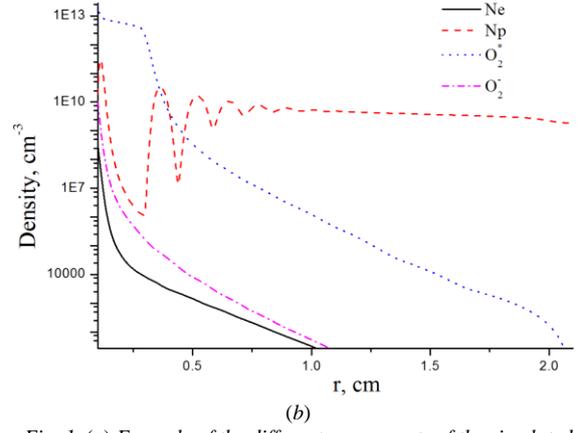
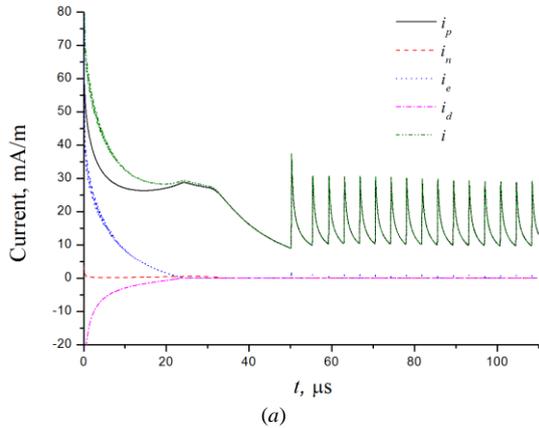


Fig. 1 (a) Example of the different components of the simulated total current i : positive ions current i_p , negative ions current i_n , electron current i_e and electron diffusion current i_d . (b) The density distribution profile at 108.46 μ s, when one of the current pulse reaches the maximum value.

In order to further validate the model, the simulation is compared with the experimental results reported in [1] for a cylindrical configuration with inner and outer radius of 0.1593 cm and 29.05 cm. In this case, the applied voltage ranged between 60 and 180 kV. Figure 2 shows the good agreement between the measured and the calculated average current in this configuration. The oscillation frequency of the stable corona current ranged from 25 to 100 kHz, which also agrees with the experimental result (about 50kHz) [1].

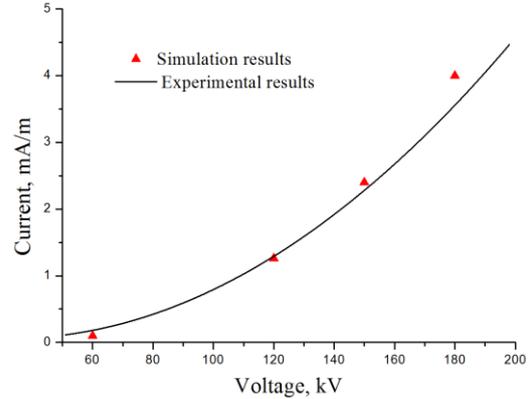


Fig. 2 Comparison between measured and simulated voltage-current characteristics for positive corona.

3. SIMULATION RESULTS

In order to estimate the condition for the glow to streamer transition, a DC voltage is first applied until stable glow corona is formed around the inner cylinder, when the corona current starts oscillating steadily as shown in Fig.1(a). After this, the simulation is continued with a voltage ramp with a different rate of rise as shown in

Fig.3. The time t_0 is defined as the instant when the current pulse reaches its minimum value.

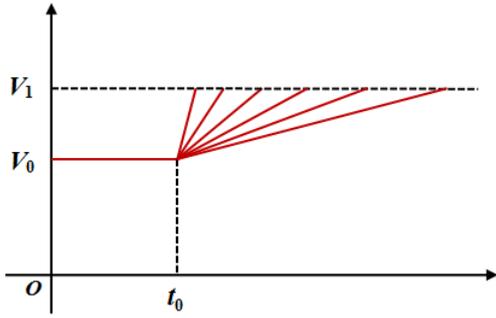


Fig.3 Waveshape of the voltage applied to the electrode configuration in the simulation.

Figure 4(a) shows an example of the simulated electric field profile for an inner conductor with 0.1 cm radius. As it can be seen, the electric field in front of the inner electrode becomes non-monotonic as the rate of rise of the applied voltage k increases. This displacement of the maximum electric field from the surface into the gap is caused by a streamer-like ionization wave. As the applied voltage rises, the positive ions do not have enough time to move away, accumulating close to the electrode surface. The maximum density of positive ions, $2 \times 10^{11} \text{ cm}^{-3}$ when $k = 0.5 \text{ kV}/\mu\text{s}$ is 10 times larger than that during the DC applied voltage ($1.9 \times 10^{10} \text{ cm}^{-3}$). Furthermore, the location of the maximum ion density in the gap displaces towards the anode surface as the rate of the voltage rise increases, as shown in Fig.4(b). This causes the distortion of the electric field, leading to the streamer inception. Observe also that there is a critical rate of rise k at which the surface electric field is smaller than the maximum electric field. This condition is assumed to define the transition from stable glow to streamers.

Table 1 lists the results of the simulation for different values of the inner and outer radius r_1 and r_2 of the conductor. The calculations are performed at a DC voltage V_0 and with a rate of rise k after t_0 . The results are also plotted in Fig.5, which compares the simulation data and the data from a best fitting equation. Further simulations with different primary applied voltages have also been performed (although not shown here) and it shows that the critical value k is independent of V_0 . Thus, the fitting of k as a function of radius r can be expressed as

$$k = 0.3r^{-0.6} \quad (6)$$

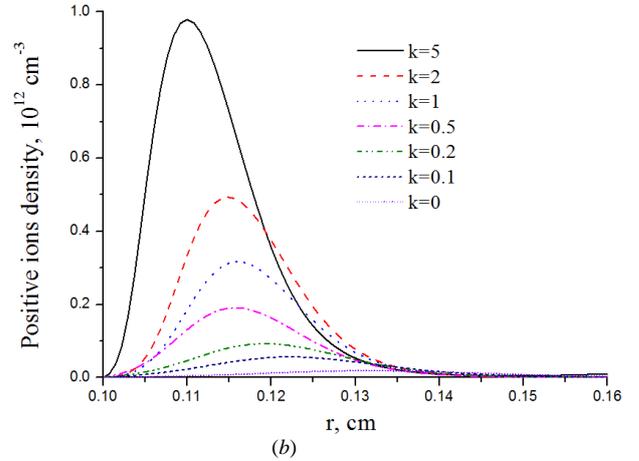
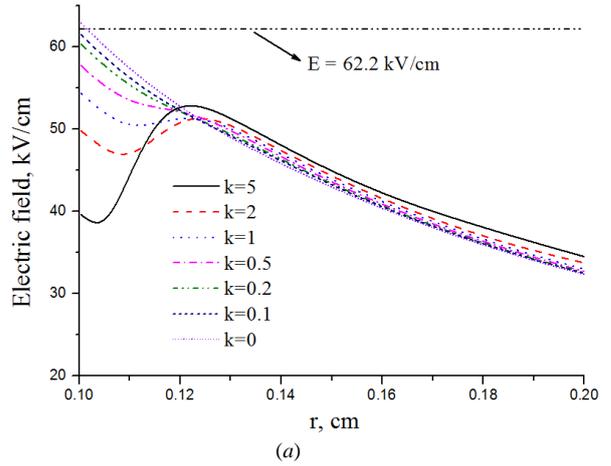


Fig.4 Comparison of the (a) electric field and (b) positive ions distribution near the anode surface for different rates of rise in $\text{kV}/\mu\text{s}$. Each curve corresponds to the time when the surface electric field on the inner cylinder reaches the minimum value during the first pulse after the rising of the applied voltage.

The critical value k varies inversely with the radius of the wire. This trend also exists in the case when the applied voltage is raised at the beginning of the corona discharge [6].

Tab.1 Simulation results with different radii

r_1, cm	r_2, cm	V_0, kV	$k, \text{kV}/\mu\text{s}$
0.01	10.01	25	5.0
0.05	10.05	40	1.8
0.1	8.1	43.3	1.2
0.1593	29.05	150	0.9
0.4	4	60	0.5
1	101	600	0.35

It is important to point out that the surface electric field during the development of glow corona under a constant background electric field is close to the onset electric field calculated by Peek's formula [7], as previously reported in [4]. For example, the onset electric field is 62.2 kV/cm for a 0.1 cm radius conductor, as shown in Fig.4(a).

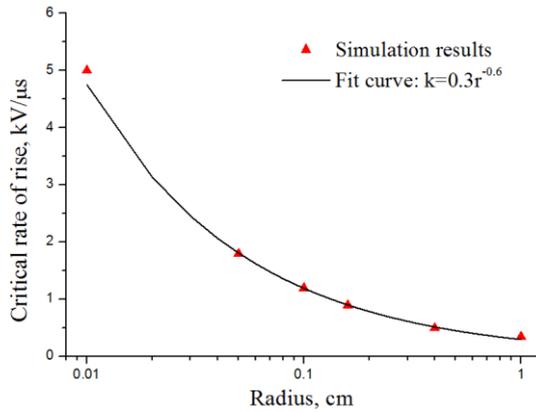


Fig.5 Simulation result of critical rate of rise for glow to streamer transition as a function of the inner cylinder radius. A best fitting curve is also shown.

However, observe that the surface electric field during a fast-changing applied voltage deviates from the onset electric field due to the accumulation of charges in the ionization layer. This casts doubts to the assumption of a constant surface electric field (equal to Peek's equation) used for the estimation of the glow to streamer transition under fast electric field rise times [8]. Unfortunately, the above-presented results still cannot lead to a conclusive statement about the validity of that assumption. For that reason, the implementation of the described model to geometries more relevant to the problem of glow to streamer transition under lightning conditions will be the subject of a future publication.

4. CONCLUSION

- a) The hydrodynamic fluid model for corona is validated by comparison with the available experimental data.
- b) Based on the numerical simulation, the critical rate of rise of the applied voltage on the wire surface for the transition from glow to streamer corona is evaluated for different radii and DC voltages. The results show that the critical rate of rise varies inversely with the radius while almost independent of the primary applied voltage.
- c) The surface electric field is close to the onset electric field calculated by Peek's equation when the applied voltage is fixed and the corona discharge is stable. However, it deviates from the onset electric field due to the charges accumulation during a fast-changing applied voltage.

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REFERENCES

- [1] R. Waters and W. Stark, "Characteristics of the stabilized glow discharge in air," *Journal of Physics D: Applied Physics*, vol. **8**, p. 416, 1975.
- [2] M. Becerra, "Glow corona generation and streamer inception at the tip of grounded objects during thunderstorms: revisited," *Journal of Physics D: Applied Physics*, vol. **46**, p. 135205, 2013.
- [3] M. Mokrov, *et al.*, "Development of a positive corona from a long grounded wire in a growing thunderstorm field," *Journal of Physics D: Applied Physics*, vol. **46**, p. 455202, 2013.
- [4] R. Morrow, "The theory of positive glow corona," *Journal of Physics D: Applied Physics*, vol. **30**, p. 3099, 1997.
- [5] L. Liu and M. Becerra, "Towards a Simple, Fast, Oscillation-free, High-resolution Algorithm for Unsteady Flows (II): Fixed Moving Particles Method," unpublished.
- [6] C. Uhlig, "The ultra corona discharge, a new discharge phenomenon occurring on thin wires," in *Proceedings of High Voltage Symposium, National Research Council of Canada, Ottawa*, 1956.
- [7] F. W. Peek, *Dielectric phenomena in high voltage engineering*: McGraw-Hill Book Company, Incorporated, 1929.
- [8] N. Aleksandrov, *et al.*, "The effect of coronae on leader initiation and development under thunderstorm conditions and in long air gaps," *Journal of Physics D: Applied Physics*, vol. **34**, p. 3256, 2001.