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TWO PEAKS OF TOTAL CURRENT IN STREAMER PROPAGATION

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The numerical simulations of the cathode directed streamer propagation in the discharge gap, with the streamer going out to cathode, are carried out. The processes are found, which take place near anode and contribute to the formation of the first of two maxima of total current time dependence. The factors are considered, which determine the propagation of the ionization process at the final stage, when the streamer approaches the cathode, and the ionization wave is propagating along the cathode surface.

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INTRODUCTION

Even at the constant applied voltage, the positive corona in atmospheric air usually operates in pulse mode, through the cathode directed streamers. From the experimental data, it follows that in positive corona the energy expense on one ozone molecule forming is less than in negative corona. Cathode directed streamer propagation is widely studied [1] and its study is continuing [2-4]. In experiments, for the streamers overlapping the discharge gap, the total current time dependence may have two maxima [4]. The numerical simulations in [5] have given the both total current maxima at the end of streamer propagation. But there are experiments, in which the time between the maxima is several tens of nanoseconds. In addition, the first maximum in the simulations was weak. And which is more, it was revealed the error in the used computer code, giving the wrong motion direction for the positive ions, and so, all results obtained in the simulations may be wrong and should be revised. In the present work, for the stage of the streamer going out to cathode, some revision is carried out in the section 2. In the section 1, the processes near anode are considered, which can lead to appearance of two total current maxima.

1. FORMULATION OF PROBLEM

Dependently on the applied voltage and other discharge parameters, the streamer can either cross the gap between electrodes or stop somewhere in the gap. The cathode directed streamer stopping approximately in the middle of the discharge gap filled with homogeneous gas seems a strange phenomenon. Indeed, at the stage when the ionization zone ahead of streamer propagates sufficiently far from the needle anode and the plane cathode, the electric field strength in the ionization zone almost does not change. And it is naturally to suppose that all streamers, which have passed the considerable part of the discharge gap, will have come to cathode. But in the experiments, it was demonstrated almost continuous change of the streamer stopping position with the applied voltage decrease, when the position is far from electrodes.

As it is supposed in [5], such possibility is connected with the presence of the rest of the streamer channel in the discharge gap. If the applied voltage is increased sufficiently slow then the distribution of free electrons and negative ions in the discharge gap before the first streamer start is determined by external sources. If the sources are uniform then in the gas with low attachment intensity the distribution of free electrons is near to linear one and the value of electron density near cathode is very small (in connection with electron drift), whereas in the gas with high attachment intensity the similar distribution is characteristic for the negative ions.

The next streamers are propagating in the gas filled with the particles, formed by the previous streamers. There are exited particles and negative ions, which may be ionized due to interaction with other exited particles or by photons or electrons with smaller energy than one necessary to ionize a molecule in the ground state. In the time intervals between streamers, the drift and recombination make the negative ion distribution in the discharge gap non-uniform along the field direction. Nearer to anode, the negative ion density is greater and there are more favorable conditions for the streamer propagation. At some distance from anode, where the negative ion density is too small, so that relevant source of free electrons is too week, the streamer may stop.

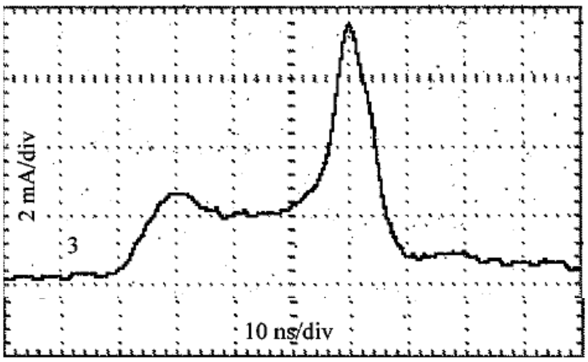

Fig. 1. Example of the total current time dependence (taken from [4])

If streamer stops in the gap far from cathode then total current time dependence has one maximum. If streamer stops near cathode then there may be two maxima in the total current time dependence, as it is in the Fig. 1 taken from [4]. In [5], the numerical simulations have shown, that the total current decrease after the first maximum takes place at the end of streamer propagation to the cathode, that is, when the distance between the streamer channel and cathode becomes minimum sufficient for the electron density increase, in avalanches, to the density value specific to the channel. Also, the simulations have shown, that the following total current increase is accompanied with appearance of large positive ion density near the cathode and with propagation of the ionization wave along the cathode surface. This wave is similar to one obtained in the simulations of the Trichel pulses [6]. But the first maximum in the simulations in [5] frequently was similar to slightly raised edge of the step before the main maximum. In addition, there are experiments, in which the time between two total current maxima is much greater than one obtained in the simulations. And which is much more, it was found the error in the used computer code, that gives the wrong motion direction for the positive ions, and all simulation results may be wrong.

2. NEAR-ANODE PROCESSES

The time evolution of the charged particle densities may be described by the equations:

$$\partial_t N_e - \mathrm{div}(D_e \nabla N_e + N_e \mu_e \vec{E}) = (\nu_i - \nu_a) N_e + R_e \,,$$

$$\partial_t N_p - \mathrm{div}(D_p \nabla N_p - N_p \mu_p \vec{E}) = \nu_i N_e + R_p \,,$$

$$\partial_t N_n - \mathrm{div}(D_n \nabla N_n + N_n \mu_n \vec{E}) = \nu_a N_e + R_n \,.$$

Here ∂_t is time derivative, the indexes e, p, and n (at the density N, mobility μ, diffusion coefficient D, and the particle production rate R) are related to electrons, positive and negative ions, $\vec{E}$ is the electric field strength, $\nu_{i,a} = \alpha_{i,a}\mu_e E$, $E = |\vec{E}|$, α_i, and α_a are the coefficients (the numbers of events per unit of electron drift path) of ionization and dissociative attachment ($\mathrm{e} + \mathrm{O}_2 \to \mathrm{O}^- + \mathrm{O}$), the terms $R_{e,p,n}$ take into account other processes of the particle production. The dependences of the coefficients α_i and α_a on the field strength have a threshold type and they are approximately described by the factor $\exp(-E_0/E)$, in which the value of E_0 is near to 180 and 45 kV / cm, respectively, for α_i and α_a. Due to such dependence, the main contribution to the perturbation of the rates of ionization and dissociative attachment (caused by a possible field strength change) give the areas in which the field strength values are near to 80…100 and 40…50 kV / cm, respectively.

If the ionization intensity in front of the streamer decreases (due to, for example, a decrease in seed electron density there) then the electron current in the channel decreases, the potential difference over the channel decreases, and the field strength outside the channel (on the parts of discharge gap between the channel and anode and between the channel and cathode) increases. The amplification of the field between the channel and cathode leads to some increase of the ionization intensity there. Such negative feedback (increase of the ionization intensity in front of streamer caused by increase of the field strength there caused by decrease of the potential drop on the channel caused by decrease of the channel current caused by decrease of the ionization intensity in front of streamer) supports the process of streamer propagation in the discharge gap at a certain level of intensity, which can change, for example, when changing, for some reason, the seed electron density in front of the streamer.

The amplification of the field between the channel and anode contributes to the intensification of ionization and dissociative attachment there, especially, in two areas, where the field strength values are near to ones mentioned above. Such source of additional positive ions is located in the space between the channel and anode nearer to anode than the source of additional negative ions.

A cloud of positive ions places between the channel and anode weakens the field between itself and the anode and strengthens the field between itself and the channel, increasing the intensity of ionization already there, with the subsequent transfer of the zone of intensification of ionization and positive ion production further from the anode, similar to what takes place near the needle anode in positive glow corona [7-9], and somewhat similar to what takes place during the usual propagation of the cathode-directed streamer in the discharge gap. Also, this positive ion cloud somewhat amplifies the field and ionization intensity in front of the streamer head. This effect corresponds to negative feedback (increase of the ionization intensity in front of streamer caused by increase of the field strength there caused by increase of the positive charge near anode caused by increase of the ionization intensity near anode caused by increase of the potential drop between the channel and anode caused by decrease of the potential drop on the channel caused by decrease of the channel current caused by decrease of the ionization intensity in front of streamer). It also somewhat helps to supports the process of streamer propagation in the discharge gap at a certain level of intensity.

A cloud of negative ions, on the contrary, strengthens the field between itself and anode and weakens the field between itself and cathode. When this cloud is located near the anode, such field redistribution leads to the fact that the perturbation of dissociative attachment, the high intensity of which falls on the mentioned range of field strength values, propagates almost only due to the drift of negative ions to the anode. The decrease of the ionization intensity in front of streamer caused by decrease of the field strength there caused by increase of negative charge near anode caused by increase of dissociative attachment intensity near anode caused by increase of the potential drop between the channel and anode caused by decrease of the potential drop on the channel caused by decrease of the channel current caused by decrease of the ionization intensity in front of streamer corresponds to positive feedback. The movement of negative ions to the anode somewhat reduces this positive feedback. The described positive feedback deepens the decrease of the ionization intensity in front of the streamer and forms the noticable peak of the total current.

But the significant strengthening of the field between the cloud of negative ions and anode (in particular, between the clouds of negative and positive ions) can lead to the process somewhat similar to breakdown of this part of the discharge gap, with the fast development of ionization, the rapid increase in positive ion number, and the following decrease of the field strength here. As a result, the interval between the streamer channel and the cathode gets much greater part of the potential difference on the discharge gap and the field strength in this interval increases. Such field redistribution can prevent the streamer stopping caused by decrease in the seed electron density in front of the streamer, and can ensure that the streamer will overlap the gap, with the formation of the second total current maximum before the finish.

Thus, the decrease of the total current (after the first maximum) caused by the decrease in the density of the seed electrons in front of the streamer, is being somewhat deepened by the positive feedback due to dissociative attachment near the anode, but later, in time, determined by the rate of development of ionization near the anode, this positive feedback destroys, and the field in front of the streamer can be amplified so, that, despite the lower density of the seed electrons in front of the streamer head, the streamer overlaps the discharge gap. The final stage of the streamer approach to the cathode is accompanied, at the beginning, by gradual increase of the total current, and then, by formation of the second maximum of the total current, much higher than the first one.

3. IONIZATION WAVE NEAR-CATHODE

When the streamer approaches the cathode the field strength in the ionization zone ahead of the streamer increases. The strength increase leads to the growth of the rates of impact ionization and radiation of the photons with the energies sufficient for the gas ionization and for the electron emission from cathode. Near the cathode, both the conductivity current and the displacement current considerably increase. The conductivity current increases due to the increase of the total rate of production of electrons, which make the main contribution to the conductivity current. The displacement current increases due to the increase of the total rate of production of positive ions, whose charge makes the main contribution to the field strength near cathode. The drift of the positive ions to cathode (up to their going out from the discharge gap) also contributes to the total current increase, but this contribution is comparatively small, as the positive ion drift velocity is small, and using of the simulations code with the wrong positive ion drift direction gives almost the same total current time dependence.

The processes just described are accompanied by the propagation of the ionization wave similar to streamer above the cathode surface by a distance of the order of transverse size of the main streamer. Of course, this ionization wave is not really axially symmetrical with respect to any line perpendicular to cathode surface and the choice of its propagation direction is determined by many factors. In any case, this wave contributes to the total current near its main maximum.

In the Fig. 2 the example of the near-cathode distributions obtained in the simulations (the symmetry axis at the bottom, cathode on the left) is shown for the electron density (a, b), charge density (c), and electric field strength (d), at the time near maximum of total current (a) and 0.2 ns before (b, c, d). The horizontal size is 0.5 mm. The color range (at the top, from blue to red, with taking the color for the nearest lesser value) corresponds to the ranges $2\cdot10^{8}\ldots2\cdot10^{16}$ cm^{-3}, $-8\ldots+24$ μC / cm^{-3}, and 20…500 kV / cm, respectively, in the logarithmic, linear, and logarithmic scales, respectively. The main source of electrons initial for the avalanche multiplication in the front of the considered wave is photoemission from the cathode. The photons absorption length in the simulations is 10 μm. Some propagation of the top of the ionization zone away from the cathode before the end of propagation is connected with the previous distribution of the space charge (c) and its field (d). The space charge near the wave front is so large and compact, that its field is sufficient for the intensive ionization not only between the charge and cathode (where the field strength is the sum of the absolute values of the contributions of real space charge and its mirror reflection in cathode), but even further from the cathode (where the field strength is the difference of the mentioned absolute values).

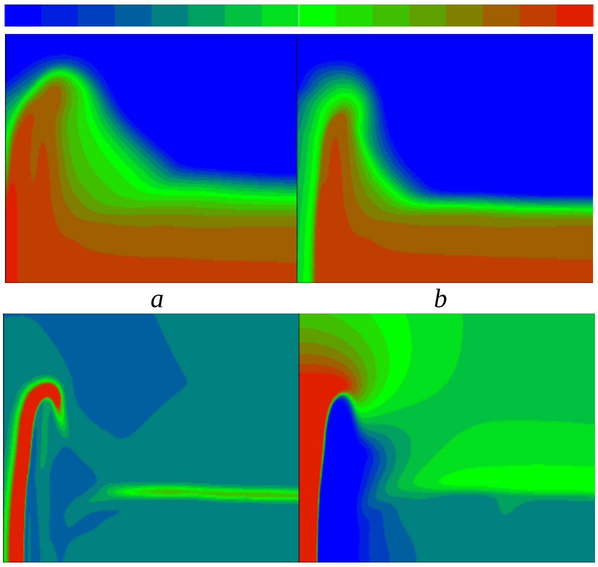

Fig. 2. Distribution of electron density (a, b), charge density (c) and electric field strength (d) in the near-cathode space at the time near maximum of total current (a) and 0.2 ns before (b, c, d)

The propagation of the ionization process to cathode leads to the decrease of the size of the intensive ionization zone. This decrease is accompanied by the field strengthening, but the local intensity (the number of events per units of time and volume) of photon radiation and electron multiplication almost does not increases because relevant coefficients (the numbers of events per unit of electron drift path) are almost independent on the field strength at so high strength level. As a result, the total rate of ionization in the ionization zone (the number of events per unit of time) decreases and leads to some decrease of both the conductivity current and the displacement current.

Further positive ion density increase in the space very near to cathode leads to further potential redistribution with the decrease of the field strength in the near-cathode space and with the end of propagation of the ionization wave above the cathode surface (as potential values in the different points of the near-cathode space become approximately equal to one at cathode). Having passed the second maximum, the total current begins to decrease.

CONCLUSIONS

In the streamer mode of positive corona discharge, in some range of the applied voltage, the total current time dependence has two maxima, and the time between them may be of the order of the total time of the streamer propagation in the discharge gap. It means thatsomewhere in the discharge gap, far from cathode, the propagation of the streamer almost stops, but then continues again. The streamer propagation process has no ‘inertia’, in the sense that its characteristics are being adjusted to the external parameter change in a few picoseconds, due to the small displacement of the large charge. And so, there should be the processes that first deepen the propagation rate decrease and then increase the rate. Suitable for the role of such processes are impact ionization and dissociative attachment in the space near to the needle-anode, which are very sensitive to the field strength change in the ranges near to 80…100 and 40…50 kV / cm, respectively. The total current decrease caused by decrease in the seed electron density in front of streamer is being somewhat deepened due to the additional decrease of field strength and ionization rate in front of streamer caused by the field of the negative charge formed near the anode due to dissociative attachment. But later, in time, determined by the rate of development of ionization near the anode, the formation of larger positive charge there amplifies the field in front of streamer so, that, despite the lower seed electron density in front of streamer, the streamer overlaps the discharge gap and comes to cathode.

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ДВА ПИКА ПОЛНОГО ТОКА ПРИ РАСПРОСТРАНЕНИИ СТРИМЕРА

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Выполнено численное моделирование распространения направленного к катоду стримера в разрядном промежутке с выходом стримера на катод. Найдены процессы, происходящие вблизи анода и способствующие формированию первого из двух максимумов в зависимости полного тока от времени. Рассмотрены факторы, определяющие распространение процесса ионизации на завершающей стадии, при приближении стримера к катоду и распространении волны ионизации вдоль поверхности катода.

ДВА ПІКИ ПОВНОГО СТРУМУ ПРИ ПОШИРЕННІ СТРИМЕРА

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Виконане числове моделювання поширення спрямованого до катода стримера у розрядному проміжку з виходом стримера на катод. Знайдені процеси, які відбуваються поблизу анода та сприяють формуванню першого з двох максимумів у залежності повного струму від часу. Розглянуті чинники, які визначають поширення процесу іонізації на завершальній стадії, при наближенні стримера до катода та поширенні хвилі іонізації уздовж поверхні катода.