TOTAL CURRENT OSCILLATIONS IN TRICHEL PULSE

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The numerical simulations of negative corona at constant voltage in air are made. Two peaks of total current in Trichel pulse in absence of photoemission appear for very small values of ion-electron emission coefficient. In presence of photoemission the total current oscillations connected with the instability based on photon radiation, photoemission, and avalanche multiplication take place.

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INTRODUCTION

The negative corona discharge in air usually operates in Trichel pulse mode. In some experimental conditions, a total current time dependence of one Trichel pulse has several maximums [1]. Before, the numerical simulations were carried out for one-dimensional particle distribution with the electric field corresponding to disks [2, 3], and for three-dimensional axially symmetric model [4]. In [3] and [4] only ion-electron emission was taken into account for the electron flow from cathode, while in [2] the photoemission also was taken into consideration. Two peaks were obtained in [2] and [3]. In [2], the first peak was accompanied with the intensive photoemission, and the second one appeared with ion going out of discharge gap. The authors [3] connected the second peak with a maximum of the conduction current at the cathode, whereas the first peak is connected with a maximum of displacement current caused by the ionization wave in discharge gap. The total current time dependence in [4] has only one maximum, although the propagation of the ionization wave towards the cathode tip was observed.

The explanation proposed in [1] and grounded on the decisive role of ionization wave, does not indicate clearly the causes of total current decrease between its maximums. The results of numerical simulations suggest two possible causes of this decrease. One of then is connected with a fast decay of the ionization wave with subsequent a slow rising of the ion current on the cathode or with field enhancement and ionization rate increase near the transverse ends of plasma region in consequence of transverse expansion of the ionization wave. Another possible cause of appearance the peaks is connected with the instability of the process based on radiation of photons, photoemission, and impact ionization.

For more detailed study of the factors, which determine the characteristics of Trichel pulses, the different dependences of the ion drift velocity on the field strength and the different values of the ion-electron emission coefficient were used. In the known papers, a constant value for the ion mobility is often used, or it is assumed that ion mobility increases with the field strength increase. Emission properties of cathode strongly depend on the chemical composition of the cathode surface during discharge, and they may be considerably different for the different experimental conditions.

1. IONIZATION WAVE AND POSITIVE ION FLOW

In the simulations carried out without taking into account a photoemission, the pulses with two peaks of the total current, and, also, the pulses with the step before the main peak were obtained, for the different dependences of the ion mobility on the field strength. Namely, the mobility decrease with the strength increase leads to two peaks, while the mobility increase leads to the step. The current increase before the first peak or before the step is connected with the development of ionization wave. The second peak and the single peak (in particular, the peak after the step) are connected with intensive going out of ions to cathode.

The ionization wave developed near cathode is somewhat similar to the cathode directed streamer, but neighborhood of needle cathode leads to some differences of this wave from the cathode directed streamer, developing in the mid-space far from the needle. The great field strength near the top of the mid-space streamer is caused by the great charge of the top, and farther from the top the strength is less. Like the mid-space streamer, the near-cathode ionization wave is accompanied with the formation of plasma region and with increase of the field strength near some part of the plasma region up to the values characteristic for streamer. But the field strength increases in the whole space between the plasma region and cathode, and the strength is greater in the part of space nearer to cathode. After formation, the plasma region expands to cathode, the distance between it and cathode decreases, and approximately the same voltage drop between the plasma region and cathode becomes correspondent to the decreased distance. As a result, in the space between the plasma region and cathode the field strength and ionization coefficient increase, and to do the same number of ionization acts an electron needs the shorter drift path. The finish of such drift with ionizations corresponds to the entering of the electron into the end of plasma region nearer to cathode with the plasma region forming in this place. In the stronger field such drift is ended at the nearer distance from the cathode. After the strength increase up to the values, at which the dependence of the ionization coefficient on the strength is slight, the development of the described ionization wave is considerably slowing down, and the displacement current considerably decreases, leading to some decrease of the total current.

The near-cathode ionization wave has some common features with the plane wave. But as cathode is a needle, the field near it is not uniform in the transverse direction, too. So, in the neighboring areas over the cathode surface, the ionization wave develops with the different rates. The development is faster in the stronger field near the needle tip, and it is slower in the weaker field farther in the direction transverse to the field strength. As a whole, the process has the form of the transverse ionization wave expansion after the considerable slowing down of its expansion along the field strength. In [4] such expansion was named ‘spreading’. The written above may be illustrated by the Fig. 1, where the electron distribution near cathode (hyperbola in the right bottom corner is the cathode surface) is shown towards the ends of the longitudinal and transverse ionization wave expansions (separated with 28 ns). In the Fig. 1, the densities are logarithmically distinguished by the black color density (range at the top, from white, 10^9 cm^{-3} or less, to black, 10^{15} cm^{-3} or greater), in the top right corners the total current time dependence is shown, and the thick vertical line in it marks the time instant. The distribution was obtained in the assumption of ion mobility decrease with field strength increase.

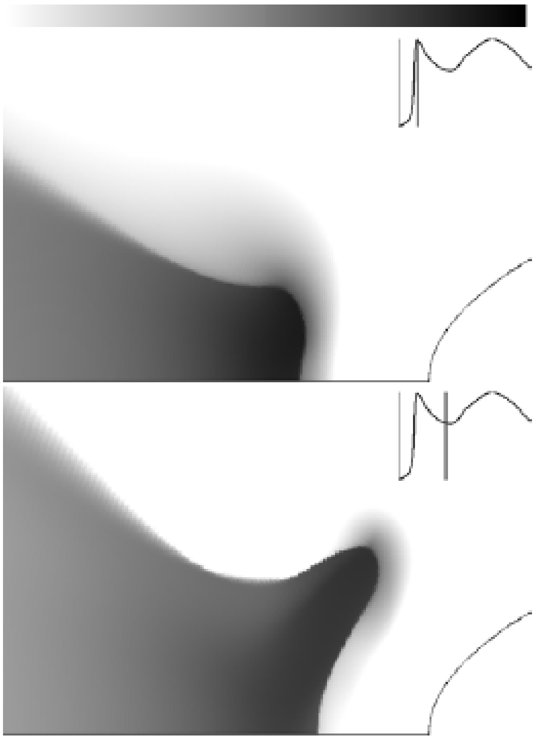

Fig. 1. Electron density near cathode towards the ends of the longitudinal and transverse ionization wave expansions in assumption of ion mobility decrease with field strength increase

With considerable increase of transverse dimension of the plasma region without considerable increase of its longitudinal width, the field strength near the transverse ends of the plasma region increases (as it takes place near the needle), and the corresponding increase of ionization rate may lead to the temporal increase of total current.

But even if the transverse expansion of the plasma region does not give considerable field strengthening near its transverse ends the second peak may arise in connection with going out of positive ions to cathode. Development of avalanches, starting by electrons from cathode forms the ion distribution, in which the density steeply increases with the distance from cathode. The going out of such distribution to cathode is accompanied with the increase of conduction current, which gives the main contribution to the total current at cathode at this stage of the pulse development. After the going out of the main part of the formed positive ions to cathode the total current decreases.

If the ion mobility in the strong field is sufficiently large then the considerable increase of the conduction current at the cathode may take place at the time of the considerable slowing down of the ionization wave longitudinal expansion, and instead of minimum between two peaks of the total current it is formed somewhat similar to the step before the main peak. Such case is illustrated in the Fig. 2 by the positive ion distribution at the beginning of the going out of their main part to cathode (and the total current step formation). The density range is the same as one in the Fig. 1, and the lines in the right corners have the same meaning. The distribution was obtained in the assumption of the ion mobility increase with the field strength increase.

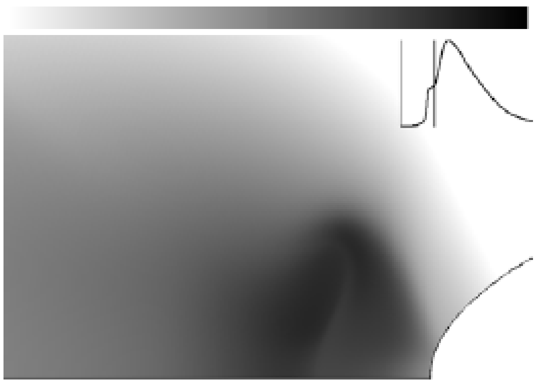

Fig. 2. Positive ion density at the beginning of going out of their main part to cathode in assumption of ion mobility increase with field strength increase

It should be pointed out that the simulations gave two peaks of the total current for the values of the ion-electron emission coefficient considerably less than the usually taken values $10^{-4}\ldots10^{-3}$. On the value of the coefficient, it is dependent how far from cathode the considerable slowing down of the ionization wave takes place. For the larger coefficient, it takes place nearer to cathode, in connection with greater electron flow from cathode. To come to the cathode from there, the ions need less time, which may to transform the first peak to the step or even to make the step before the main peak practically absent, as it has happened in the simulations [4].

It should be also pointed out that the time interval between the peaks of total current obtained in the simulations for the considered conditions (atmospheric pressure, needle tip curvature radius 50 μm) is a few tens of nanoseconds. Such time co-ordinates with one obtained in the simulations [2], but it is too large, in comparing with one obtained in the experiment [1].

2. OSCILLATIONS WITH PHOTON PARTICIPATION

If photoemission is considerable then the process of the expansion of plasma region to cathode practically stops when the space with the strong field is decreased to the dimensions not sufficient for the self-consistent process development on the base of photon radiation, photoemission, and impact ionization. But the transverse expansion of the plasma region with the field enhancement near its ends may give the total current increase and its second peak forming.

Moreover, even a few maximums of total current may be formed, in connection with two effects: (1) enlarging of ionization rate in the part of space and photon radiation from there when the electric field strength there increases, (2) increase of the electric field strength in front of the cloud of electrons, which were knocked out from cathode by photons and are moving away from cathode. The decrease of the field strength in the same part of space after the electron cloud displacement leads to the decrease of the rates of ionization and photon radiation there.

In some conditions, perhaps, somewhat artificial, the oscillations may be found out even in absence of the impact ionization, only on the base of the processes of photon radiation from discharge space and photoemission from cathode. As an example, it may be considered the model, in which only two spaces in zone of intensive photon radiation are accounted: the space c near cathode, and the space b somewhat farther from cathode. Negative charge disposed in the space b weakens the field in the spaces c and b, whereas one disposed in the space c weakens the field in the space c and strengthens the field in the space b. It may be so, that at the field strength values characteristic for the space c, the photon generation frequency is great, but its sensitivity to the strength value is comparatively low, whereas at the strength values characteristic for the space b the mentioned sensitivity is comparatively high. In the frames of the considered model, the process development may be described with the following equations:

$$\partial_t N_b = \nu_c N_c - \nu_b N_b ,$$

$$\partial_t N_c = f_c(N_c, N_b) N_c + f_b(N_c, N_b) N_b - \nu_c N_c .$$

Here ∂_t is time derivative, the indexes c and b indicate the mentioned spaces, ν_c and ν_b are the quantities reciprocal to the characteristic time of electron removing from the relevant space, N_c and N_b are electron densities, f_c and f_b are photon generation frequencies. The written equations may be considered as simplification of the equation

$$\partial_t N + \mathrm{div}(N\vec{u} - D\nabla N) = Nf ,$$

(where $\vec{u}$ is drift velocity, D is diffusion coefficient) for the mentioned spaces after the averaging over them and the neglecting of electron incoming from the other spaces. Searching for solution in the linear approximation, one puts $N_a = N_{a0} + N_{a1}\exp(\nu t)$, where the index a stands for c or b, the index 0 indicates a stationary value, and the index 1 indicates a perturbation, which is assumed to be small. Let us put $f_a^{(0)} = f_a(N_{c0}, N_{b0})$ and use the designations $f_{ac}^{(1)}$ and $f_{ab}^{(1)}$ for the values of $(\partial/\partial N_c) f_a(N_c, N_b)$ and $(\partial/\partial N_b) f_a(N_c, N_b)$, respectively, at $\{ N_c = N_{c0},\ N_b = N_{b0} \}$. For the stationary values, one can obtain the equations

$$(\nu_c - f_c^{(0)}) N_{c0} = f_b^{(0)} N_{b0} ,\ \nu_c N_{c0} = \nu_b N_{b0} ,$$

and the condition $\nu_c f_b^{(0)} + \nu_b f_c^{(0)} = \nu_c \nu_b$ of their nonzero solution existence. For the perturbations, in the linear approximation, one gets the equations

$$(\nu + \nu_c - f_c^{(1)}) N_{c1} = f_b^{(1)} N_{b1} ,\ (\nu + \nu_b) N_{b1} = \nu_c N_{c1} ,$$

where $f_a^{(1)} = f_a^{(0)} + N_{c0} f_{ca}^{(1)} + N_{b0} f_{ba}^{(1)}$. The condition of their nonzero solution existence may be written in the form $(2\nu + A)^2 = B$, where $A = \nu_b + \nu_c - f_c^{(1)}$, $B = (\nu_c - f_c^{(1)} - \nu_b)^2 + 4\nu_c f_b^{(1)}$. If the inequality $A > 0$ is held then an accidental perturbation is dumping. If $A < 0$ then the instability takes place. If $B > 0$ then the process is monotonous, if $B < 0$ then it is oscillatory. It is assumed $f_{cb}^{(1)} < 0$, $f_{bb}^{(1)} < 0$, $f_{cc}^{(1)} < 0$, and $f_{bc}^{(1)} > 0$, according to the influence of negative charge disposition on the field in the corresponding space. For the instability, it is necessary to hold the inequality

$$f_c^{(0)} + N_{b0} f_{bc}^{(1)} > \nu_b + \nu_c - N_{c0} f_{cc}^{(1)} .$$

For the oscillatory process development the inequality

$$4\nu_c(-N_{c0} f_{cb}^{(1)} - N_{b0} f_{bb}^{(1)}) > 4\nu_c f_b^{(0)} +$$
$$+(f_c^{(0)} + N_{b0} f_{bc}^{(1)} + \nu_b - \nu_c + N_{c0} f_{cc}^{(1)})^2$$

has to be held. In particular, if the value of $f_c^{(0)} + N_{b0} f_{bc}^{(1)}$ is sufficiently large then the process is unstable. And if, in addition, the value of $-N_{c0} f_{cb}^{(1)} - N_{b0} f_{bb}^{(1)}$ is sufficiently large then the instability is oscillatory.

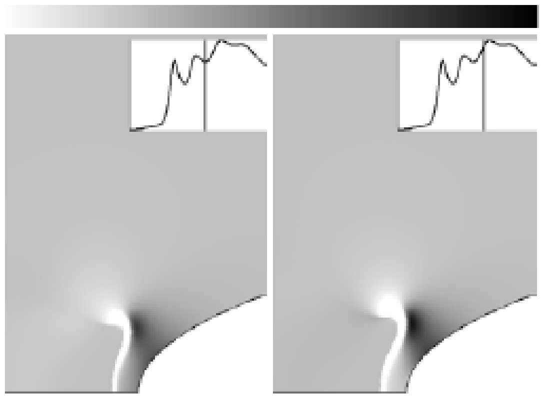

Fig. 3. The rates of the field strength change at the instants with the different rates of the total current change

In the presence of impact ionization, the instability based on the photon generation and electron emission may be considerably enhanced due to electron multiplication. Intervals between maximums correspond to the time of electron drift from the cathode to the space of intensive photon radiation near the plasma region. This time is considerably less than the time of positive ion drift from plasma region to cathode, and it corresponds to the time between peaks of total current obtained in the experiment [1]. In the Fig. 3, the rates of the field strength change are shown for two instants separated with 0.5 ns. The total current changes slowly near the first of them, and increases rapidly near the second. The color scale range is from $-5\cdot10^{13}$ to $+15\cdot10^{13}$ V/(cm·s). The lines in the right corners have the same meaning as ones in the Fig. 1. The time derivative of the field strength in the space near the transverse end of the plasma region is positive, which is partly connected with the ionization wave expansion in this direction. But once in a while the rate of the strength change there increases additionally, due to the next approach of the increased number of electrons, which were obtained as consequence of the previous such approach, through the increase of photon radiation from the space, electron emission from cathode, and electron multiplication in avalanches. The field near the plasma region is not so strong as one near the cathode surface, the photon generation frequency there is less, but sensitivity of the frequency to the strength value is higher, and the product of the great (through multiplication) number of electrons and the comparatively small photon generation frequency gives the photon generation rate, which is considerable and highly sensitive to the strength value, so that the comparatively small oscillations of the field strength near the plasma region leads to the considerable oscillations of the total current.

CONCLUSIONS

With the aid of the numerical simulations some details of Trichel pulse development are obtained. During the transition from the simple avalanche multiplication to the ionization wave set up, the total current usually changes monotonously without any temporary decreases. The minimum after the first maximum obtained in the simulations is connected with considerable slowing down of longitudinal expansion of ionization wave and with the following increase of conduction current of positive ions at cathode. In the case of fast coming of positive ions to cathode, the step before the main peak may be formed, without a temporary decrease of the total current. Several total current maximums with time intervals of order of nanosecond obtained in experiments, probably, are connected with the instability of the process based on the photon radiation from the discharge space, photoemission from the cathode, and electron multiplication through impact ionization. The instability arises due to electric field enhancement in front of the part of electron flow having enlarged density, which moves away from cathode to the space of intensive photon generation near the end of plasma region, and due to the consequent increase of photon generation rate there, which leads to formation of new enlarging of the density of the part of electron flow through photoemission.

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КОЛЕБАНИЯ ПОЛНОГО ТОКА В ИМПУЛЬСЕ ТРИЧЕЛА

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Выполнено численное моделирование отрицательной короны при постоянном приложенном напряжении в воздухе. Два пика полного тока в импульсе Тричела при отсутствии фотоэмиссии появляются при очень малых значениях коэффициента ионно-электронной эмиссии. При наличии фотоэмиссии имеют место колебания полного тока, связанные с неустойчивостью, основанной на излучении фотонов, фотоэмиссии и лавинном размножении.

КОЛИВАННЯ ПОВНОГО СТРУМУ В ІМПУЛЬСІ ТРИЧЕЛА

О. Болотов, В. Голота, Б. Кадолін, С. Маньковський, П. Марков, В. Остроушко, І. Пащенко, Г. Таран, Л. Завада

Виконано числове моделювання негативної корони при постійній докладеній напрузі в повітрі. Два піки повного струму в імпульсі Тричела за відсутності фотоемісії з'являються при дуже малих значеннях коефіцієнта іонно-електронної емісії. За наявності фотоемісії мають місце коливання повного струму, що пов'язані з нестійкістю, яка ґрунтується на випромінюванні фотонів, фотоемісії та лавинному розмноженні.