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Repulsion effect in orientation of «lightning» discharge

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Abstract. — The phenomenon of repulsion of «lightning» discharge channel by an isolated conducting object is investigated experimentally. Experimental results by the display of charging of isolated object with a positive charged streamer are explained.

1. Introduction.

It is known that the following factors influence the orientation of leader channel in a space: gap geometry, characteristics of leader, atmospheric conditions, etc. Many papers (see, for example, [1-2]) were devoted to investigation of striking probability dependence on the conductivity and capacity of isolated objects. In [1] it is shown that the striking probability of objects grows with the increase of its conductivity and capacity. In [2] the dependence of striking probability on the situation of objects in a gap is investigated. It is shown that the striking probability grows near the earth surface. In [3] the influence of the polarity of discharge on the striking probability of spheres was studied. The orientation of leader channel is usually supposed to be determined by the degree of field intensification. However, this approach does not allow to take into account for a number of physical effects influencing on the striking probability of objects. In particular, the processes of interaction between the charges of leader and object in the final stage of orientation, when the front of streamer zone approaches to the object, are not taken into consideration. Investigation of striking probability dependence on the charge of leader also represents a practical interest for the lightning protection of aircrafts.

In this paper the investigation of positive leader interaction with the isolated conducting objects is carried out. It is found that the leader channel primary orientating on the object, later on drives round it in a distance shorter than the streamer zone length of leader. The threshold dependence on the capacity of object and the charge of streamer zone of leader is revealed. This result is unexpected and interesting, since at the approach of leader to such distance, according to the existing notions, the discharge channel orientates on the object, independently of discharge parameters.
2. Experimental results.

Experimental investigations were conducted in the rod-plane gap at the influencing of switching impulses of positive polarity $15/7 \times 500 \mu s$ and $300/7 \times 500 \mu s$. Earthing electrode is the metallic surface with dimensions $18 \times 18$ m. The switching impulses were formed in the output of high voltage generator HVG-9 mV with summary voltage $9$ mV and energy capacity $1.35$ mJ. The generator allows to obtain spark discharges with length right up to 100 meters.

The striking probability of conducting spheres with different diameters in the dependence on theirs situation in the gap and the parameters of leader was determined. The spheres with the diameters $D = 4, 10, 30, 50$ cm were used. The spheres were situated in the gap at the different distances from the rod end both inside the streamer zone and outside of it. The length of streamer zone was measured using the image converter camera, which allows to register a light radiation in a spectral range from $0.38$ to $0.75$ μm in both instantaneous and continuous regimes. The exposition time of device is changed from $1$ μs to $10\,000$ μs. So, at the gap length $d = 6$ m and the durations of applied voltage front $\tau_f = 300$ μs and $\tau_f = 15$ μs the streamer zone length is equal to $L_{str} = 0.6$ m and $L_{str} = 2$ m, accordingly. In figure 1 a typical image convertor record of the positive discharge phenomenon is presented. It is seen, that as distinct from the region, occupied by the streamer zone, the leader channel shines weakly at its propagation.

The intensity of electric field in the streamer zone was measured using the Pockels device. The sensor is a primary transducer optically connected by fiber guides of up to 150 m long with a light source and a photodetector. Recorded frequency band is $50$ mHz. Detailed description of electric field measurements is given in papers [4, 5].

Fig. 1. — A typical image convertor record of the positive discharge for an impulse shape applied to the $8$ m gap ($15/7 \times 500 \mu s$).
The trajectories of spark channel were photographed using two cameras, placed under the angle 90°. Striking probability of spheres were determined from the most of 100 discharges for each case. In figure 2 the dependences of a striking probability of the spheres with different diameters on the distance between the sphere and rod at the applied voltage $\tau_f/\tau_i = 300/7 \, 500 \, \mu s$ are presented. For the comparison, the curve corresponding to the aircraft model with length 1.15 m also is presented. Analogical dependences were also obtained for the applied voltage 15/7 500 μs. It is seen from the figure, that the striking probability may be either increasing or decreasing function of the distance between the object and high voltage electrode at various object sizes. Notice that the increase of striking probability begins from a distance to the earth smaller than the streamer zone length in the final jump phase. The streamer zone lengths in the final jump phase equal to $L_{st} = 2.1 \, m$ at the applied voltage 300/7 500 μs and $L_{st} = 3 \, m$ at the applied voltage 15/7 500 μs in a gap with length $d = 6 \, m$.

Fig. 2. — Trajectories of spark discharge in a gap with a free potential object, placed on the distance $s$ from the rod. a) $s = 0.6 \, m$, $D = 10 \, cm$, $\tau_f/\tau_i = 300/7 \, 500 \, \mu s$; b) $S = 1.2 \, m$, $D = 30 \, cm$, $\tau_f/\tau_i = 15/7 \, 500 \, \mu s$; c) $s = 6 \, m$, $D = 30 \, cm$, $\tau_f/\tau_i = 15/7 \, 500 \, s$.

Striking probability of the spheres smaller than the definite size equal to zero even at the approaching of its to the rod on a distance order of sphere diameter. Hence it follows that the effect is not connected with the chance orientation of leader trajectory in a space. Note that the striking probability of objects with a dimension larger than the streamer zone length is equal to 100 % when they are placed on the boundary of streamer corona and inside of it. The repulsion effect becomes essential in the vicinity of critical values of object capacity and charge of leader and besides the objects are not struck by a leader with a charge more than the critical one. So, the striking probability of the sphere with a diameter $D = 50 \, cm$ by a leader with the charge of streamer zone $Q_{str} = 2.5 \, \mu C$ is equal to $P = 30 \, %$, but at $Q_{str} = 4.5 \, \mu C$ the striking probability of this sphere equals to zero.

In figure 3 photographs of discharge trajectory in the gap with length $d = 6 \, m$ are presented. For visual, the pictures for which the projection of trajectory in the perpendicular plane practically pass on the axis line of gap are choosed. It is seen from the figure, that the trajectory of leader rounds the sphere in a distance shorter than the streamer zone length.
Fig. 3. — Striking probability $P$ as a function of distance between the rod and object. 1 — $D = 4$ cm; 2 — $D = 10$ cm; 3 — $D = 30$ cm; 4 — $D = 50$ cm; 5 — aircraft model.

3. Physical picture.

It is known [6] that the trajectory of spark channel is completely determined by the trajectory of leader head. The trajectory of leader head passes within the boundary of top angle of streamer zone. Therefore the cause of rounding of object by the leader is the changing of streamer zone orientation because of its interaction with the object. It is known also [7], that the streamers starting from the leader head keep the galvanic connection with it only up to order 1-2 cm. The maximum length is determined by the disintegration time of plasma owing to recombination processes or the loss of conductivity in the old parts of streamer channel. This time in air is equal to $\tau_d = 10^{-7}$ s, i.e. the length of streamers composes $\ell = 2$ cm at its velocity of propagation $v_s = 2 \times 10^7$ cm/s [7]. Streamer zone length in the investigated gaps composes a value of order one meter and more. Therefore the propagation of streamers in the streamer zone takes place at the absence of galvanic connection with the leader head, i.e. the streamer zone represents something as a badly conducting medium, consisting of needle form plasma formations. The physical picture in the final stage of leader orientation, when the front of streamer zone contacts with an object, is analogical to the charging of noncharged conducting object in the external electric field with the positive ions. However a mechanism of charge transfer from the streamer zone to the sphere is not caused by the drift of positive ions in the electric field. The positive charge is transferred by the streamer plasma formations (needles), the velocity of propagation of which $v_s$ in the field $E_{str}$ is essentially more than the velocity of positive ions in that field ($v_s > 10^7$ cm/s). This velocity is determined by the ionization processes in the front of streamers $v_s = \alpha \cdot v_0 r_0$, where $\alpha$ is the ionization coefficient, $v_0$ is the drift velocity of electrons, $r_0$ is the radius of streamer head [8]), where a great intensification of electric field exists.

A qualitative picture of leader orientation may be described in the following way. Far from the object the leader channel does not feel its availability and the change bendings of trajectory may be described in the frame of Laplas fractal model [9]. From the distance $H$ a propagation of leader takes place mainly in the direction of field intensification, created by the object (Fig. 4). At the contact of streamer zone ($h = L_m$) with the object is latter charged by the positive charge. This decreases the flow of electric field, closed on the object (Fig. 5). If that charge turns out to be more than the induced negative charge, then the
Fig. 4. — Schematic representation of leader discharge orientation 1 — rod, 2 — leader channel, 3 — head of leader, 4 — streamer zone, 5 — free potential object, 6 — plane electrode.

repulsive field appears. This explains the existence of threshold dependence of repulsion effect on the dimension of object and charge of leader. The electric field on the surface of sphere may be presented in the form:

\[ E = E_1 + E_2 = 3 E_0 \cos \theta - \frac{Q}{\pi \varepsilon_0 D^2}, \]  

(1)
where $E_1$ is the electric field on the surface of sphere in the external field $E_0 = E_{str}$, $E_2$ is the repulsive field, $Q$ is the charge on the sphere, $\varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$.

The electric field flow coming into the sphere is equal to

$$
\Psi = \oint E \, dS = \frac{3\pi D^2 E_0}{4} \left(1 - \frac{Q}{3\pi \varepsilon_0 E_0 D^2}\right)^2 = \frac{3\pi D^2}{4} E_0 \left(1 - \frac{Q}{4Q_{in}}\right)^2
$$

(2)

It is seen from here, that the maximum charge acquired by the sphere is equal to $Q_{max} = 3\pi \varepsilon_0 E_0 D^2 = 4Q_{in}$, where $Q_{in}$ is the induced negative charge on the sphere, determined by the capacity of object.

The charge carried by the streamer zone of leader, may be evaluated owing to the known value of electric field intensity in the streamer zone, using the Gauss theorem:

$$
Q_{str} = \varepsilon_0 \oint E_{str} \, dS = 2\pi \varepsilon_0 E_{str} L_{str}^2 \left(1 - \cos \frac{\Omega}{2}\right).
$$

(3)

The electric field intensity in the streamer zone is constant along the all length of it and composes $E_{str} = 5 \text{ kV/cm}$ [5].

Therefore from the Poisson equation div $E = 4\pi \rho$ it follows, that the charge density in streamer zone changes as $\rho \sim 1/\rho$ with a distance from the head of leader, i.e. the main space charge is concentrated in the front region of streamer zone [8]. The top angle of streamer zone is changed usually in the range 30°-90°. The streamer zone length $L_{str}$ grows with the increasing of gap length and in the lightning discharge may compose a few ten meters [10]. The charges of streamer zones with lengths $L_{str} = 0.6 \text{ m}$ and $L_{str} = 2 \text{ m}$, calculated using the formula (3), are equal accordingly to $Q_{str} = 3 \mu\text{C}$ and $Q_{str} = 33 \mu\text{C}$ at $\Omega = 90°$. In the electric field of streamer zone the induced charge on the sphere with a diameter $D = 50 \text{ cm}$ is equal to $Q_{in} = 2.6 \mu\text{C}$.

Comparing the charge of streamer zone with the induced charge, we obtain $Q_{str}/4Q_{in} = (2/3) \times L_{str}^2 \left(1 - \cos \frac{\Omega}{2}\right)/D^2$, i.e. the effect of repulsion becomes essential ($Q_{max} < Q_{str}$) when the condition $D < \sqrt{(2/3) \times \left(1 - \cos \frac{\Omega}{2}\right)} \times L_{str}$ is carried out. So far as the coefficient $\sqrt{(2/3) \times \left(1 - \cos \frac{\Omega}{2}\right)}$ is smaller than unity, then $D < L_{str}$ which agrees with the experimental data.

4. Discussion.

Note that a picture of leader orientation added above does not take into account the corona processes and the developing of contrary discharge from the objects, equipped with a nail, where the critical value of field intensification $E_{cr} = 30 \text{ kV/cm}$ is reached. An intensification of field in the case of sphere is compared $E = 3E_0 = 15 \text{ kV/cm}$ [11], i.e. the corona processes are not started. Experiments showed that the striking probability of sphere equipped with a nail essentially depends on the location of nail on the sphere. A cathodic nail does not influence the striking probability of sphere. So, the sphere of a diameter $D = 50 \text{ cm}$ with a cathodic nail 10 cm long, placed on the distance $s = L_{str}$ from the rod, was not struck in general but the same sphere with an anodic nail is struck with the probability 100 %. Essential influence of the anodic nail on the striking probability of sphere with a diameter $D = 8 \text{ cm}$ is noted also in paper [3]. The corona processes may cause also the increasing of
striking probability near the earth surface, when an object turns out to be in the streamer zone during the final jump phase.

Note that the induced charge may not be compensated by the charge of the streamer zone at the situation of object on the earth surface. Therefore the striking probability of sphere in this case is not equal to zero (Fig. 3c).

Thus, the experimental results may be explained by the display of charging of isolated object with the positive charged streamers. The present theory predicts the increase of attractive area of leader channel as the availability of corona processes from the object, which agrees with experimental results.

References


Proofs not corrected by the authors.