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Abstract

Full Text

TECHNICAL PHYSICS

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INVESTIGATION OF THE MECHANISM OF THE NEGATIVE SPARK

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Earlier the authors described ^(1,2) the development of a spark in a rod-plane gap $-c + p-$ with length up to $S_0 = 3$ m under a voltage wave of $1.5/1000 \mu\text{sec}$, and introduced terms for the various elements of the spark. Here the mechanism of the spark in a $c + p$ gap is investigated for exponential voltage waves, which may be characterized by the average steepness A , for example between $t = 0$ and $t = 2.3R_\phi C_\phi$. The change in steepness at the wave front itself does not exert a substantial influence on the discharge processes. Reducing A to $100 \div 250$ $\text{kV}/\mu\text{sec}$, as compared with the standard wave, where $A = 600 \div 1000$ $\text{kV}/\mu\text{sec}$, leads to a change in the discharge processes in the gap. From Fig. 1 I it is seen that the impulse corona (i.k.), arising at the beginning of the discharge, has a length of no more than 25 cm. Then the stepped leader of the spark develops. Up to t_1 , $A_1 = 160$ $\text{kV}/\mu\text{sec}$, and the effective velocity of the stepped leader is $1.2 \cdot 10^7$ cm/sec ; the velocity of the negative leader developing in its channel is $\simeq 1.4 \cdot 10^6$ cm/sec . In the interval $t_2 - t_1$, $A_2 = 40$ $\text{kV}/\mu\text{sec}$, and after t_2 the steepness decreases still more. The amplitude of the voltage wave was somewhat less than U_p , which led to cessation of the advance of the stepped leader. Fig. 1 II illustrates the process at a later stage; here the voltage amplitude $U \geq U_p$. In the static picture preceding the triggering of the time sweep, several channels of the stepped leader are distinguished, around which the branches of the i.k. are visible, which had occurred during its advance. After t'_0 only the elongation of channel ab is noticeable. The i.k. branch arising from b_1 from the instant t'_1 , as it develops, reaches the plane. At the same time, upward along the channel of the stepped leader, with a velocity of $1.3 \cdot 10^8$ cm/sec , waves of luminosity are successively propagated ⁽¹⁾. By t_2 , when the channel of the stepped leader has grown through to the plane, a positive leader is formed from it (its initial velocity is $1.2 \cdot 10^7$ cm/sec); now luminosity flashes throughout the entire gap. This filamentary luminosity (the filaments are probably traces of luminous spheres moving with velocities of the order of $> 10^8$ cm/sec —of the type of the Park and Cones mechanism ⁽⁵⁾) connects the heads of the positive and negative leaders. Closure of the shutter of the electro-optical converter occurred at t'_3 .

In ⁽²⁾ the detection in the channel of the stepped leader of a spark of a detached channel developing simultaneously upward and downward was noted. The development of such channels is also observed on exponential voltage waves. In

Fig. 4. Diagram of the development of a negative spark in the gap $-c + p$ on exponential (oblique-front) voltage waves.

Figure 1: Fig. 4. Diagram of the development of a negative spark in the gap $-c + p$ on exponential (oblique-front) voltage waves.

Fig. 2* from the instant t_1 , in the channel of the stepped leader advancing farther, a detached channel develops from point P in the direction of points m and n , henceforth called a **volume leader**. The length of the channel increases on both sides from P (Fig. 2). The velocity of the upper (positive) head of the volume leader is of the order of $3 \cdot 10^6$ cm/sec, and that of the lower (negative) head is $0.3 \cdot 10^6$ cm/sec. The velocity of the head of the negative leader (from the electrode) is $\simeq 0.3 \cdot 10^6$ cm/sec. At the instant t_2 the positive head of the volume leader at point m joins with the negative leader. Simultaneously, an intense i.k. is formed from the lower head of the volume leader at point n . As a re-

* The curvature of the sweep line is a defect of the electro-optical converter.

as a result of the processes described, the channel of the negative leader increases stepwise by the length of the space leader (see insert, p. 1071).

For $A < 40$ kV/ μ sec the development of the spark proceeds in a new form: at certain time intervals there occur successive flashes of the i. c. with simultaneous elongation of the leader channel from the rod (Fig. 3 I). This leads to the fact that, from a certain moment on, the development of the spark will be analogous to the development of a spark on a standard wave. The picture of the transition of the process to this stage is recorded in Fig. 3 II; the sweep was started at the moment t_0 , before which several flashes of the i. c. had formed in the gap, with elongation of the leader channel; this stage has the form of a static image at the beginning of the oscillogram. From the moment t_1 , a space leader develops from point c , merging at point d at the moment t_2 with the channel already existing at the electrode. The potential of the negative head of the space leader at point b changes abruptly to a value close to the potential of the electrode, and from it an i. c. arises. Although here it does not reach the plane, it creates conditions for the further development of the stepped leader of the spark, which, moving toward the plane, causes a counter leader. The later stages of this development are visible in Fig. 3 III. Here the positive and negative leaders develop with approximately the same and ever-increasing velocity. Closing of the e.o.p. shutter occurred at t_1 , before the leaders met.

Fig. 4. Diagram of the development of a negative spark in the gap $-c + p$ on exponential (oblique-front) voltage waves.

$I - A = 250 \div 100$ kV/ μ sec; $1a$ —primary i. c.; $1b$ —secondary i. c.; 2 —stepped leader of the spark; $2a$ —step—the stem of the i. c.; $2b$ —branches of the i. c.; $2v$ —channel; 3 —negative leader; 4 —positive leader; 5 —filamentary glow (corona of the leaders); 6 —final jump; 7 —main channel; 8 —arc. II —at $A = 100 \div 50$

kV/ μ sec: 1 –i. c.; 9 –space leader; 10 –flash of the leader channel; the remaining designations are the same as for diagram *I*. *III* –at $A < 40$ kV/ μ sec; *3a* –push-like negative leader; the remaining designations are the same as for diagrams *I* and *II*.

The materials obtained make it possible to outline the principal schemes (Fig. 4) of the development of a negative spark in the gap $-c + p$ for $S_0 = 1.5 \div 2.0$ m, corresponding to definite ranges of A of the voltage wave applied to S_0 . The schemes are averaged representations of spark development, compiled on the basis of a large number of oscillograms.

Experimentally we have established that, just as for the gap $+c - p$ (^{3,4}), in the gap $-c + p$, at least for $S_0 = 1.0 \div 1.5$ m, the volt-second characteristic has a U-shaped character with a minimum U_p in the region 20–40 μ sec. Let us note that in the region t_p greater than 20 μ sec.

a considerable scatter of U_p and t_p is observed for each applied wave.

Fig. 4 I shows the development of the spark at $A = 250 \div 100$ kV/ μ sec. At the critical voltage U_k , a primary i.c. arises from the rod, having branches of small length. Then, as U increases, new i.c. elements are formed (repeated i.c.); both types of i.c. form near the rod a certain zone of space charge which, however, is considerably smaller than in the case of a 1.5/1000 μ sec wave (¹). A further increase in U leads to the development of a stepped leader, in the channel of which a negative leader grows from the rod toward the plane. The phenomena described are accompanied by current pulses measured in the plane. The mechanism of the stepped leader of the spark may, to a first approximation, be described as follows. The i.c. that has flashed up on the rod introduces a negative charge into the discharge gap, the greatest density of which is created at the boundary of the branches. The gradients here reach a critical value, which leads to the development of new discharge processes. Owing to the removal of negative charge by new i.c. flashes in the region of its occurrence, a positive space charge is exposed. Electrons flow to it from the near-electrode zone and neutralize it, which increases the gradients in the zone of the displaced negative charge. Thus begins the introduction of negative charge by the channel of the stepped leader. With each successive lengthening of the channel, an i.c. arises from its head, carrying away negative charge. Electrons flow to the positive charge thereby exposed along the stepped-leader channel from the electrode, which causes ionization accompanied by waves of luminosity in the direction toward the rod (^{1,2}). After the channel of the stepped leader touches the plane, a positive leader arises from it; its initial velocity is $\approx 10^7$ cm/sec. The heads of both leaders are connected by a filamentary glow; ionization takes place along the entire length of the gap, propagating from the positive leader to the negative one in the form of waves of luminosity; “through conductivity” is created, leading to equalization and a rapid increase of the leader velocities. Between the leader heads the gradients become equalized and increase as the leaders approach to a value leading to the final jump (⁶). The effective velocities of the stepped leader are $(0.7 \div 1.2) \cdot 10^7$ cm/sec; the velocities of the negative leader before

the appearance of the positive leader are $(0.8 \div 2.1) \cdot 10^6$ cm/sec. Thus, at $A = 250 \div 100$ kV/ μ sec, breakdown in the left-hand part of the volt-second characteristic is carried out in stages: 1) primary and repeated i.c.; 2) stepped leader; 3) negative leader developing simultaneously with the stepped one; 4) positive leader, which is connected through a corona with the negative leader; 5) final jump; 6) main channel.

At $A = 100 \div 50$ kV/ μ sec (Fig. 4 II)—the region close to the minimum U_p —the beginning of the discharge is analogous to the scheme of Fig. 4 I. However, when the stepped leader is still at a considerable distance from the plane, there occurs the formation and development in the channel of the stepped leader of a “volume leader.” To explain the development of the volume leader it may be assumed that below point P , when a pulsed corona carrying away negative charge arises, an excess positive charge is formed. If it is assumed that the stem of the preceding step has retained sufficient conductivity, then it may play the role of a point from which, in the field of the space charges of the stepped-leader channel, the channel of a volume leader will develop. The heads of this channel move along the paths Pm and Pn . The velocity of the negative head of the volume leader is close to the velocity of the negative leader, while the velocity of the positive head exceeds it. At this stage the volume leader replaces part of the stepped-leader channel, and negative charges pass through it to the head of the stepped leader. At the moment when the head m of the volume leader meets the negative leader, the length of the latter is increased by the well-conducting segment mn ; the electrode potential is rapidly transferred to point n , and an intense i.c. is formed from it. This process is similar to the pri-

application of a steep-front potential wave to the “rod” inserted into the gap. If the instantaneous voltage across the gap is sufficient to break down a section of the gap of length $l = S_0 - kn$, the breakdown is completed according to the scheme for a standard voltage wave. (If, however, as occurs in Fig. 4 III, the space leader developing from point P_1 cannot create the necessary conditions, breakdown does not occur.) In cases where the branches of the i.c. arising during bridging do not reach the plane, a stepped leader occurs. Contact of the latter with the plane causes a positive leader. Then the leaders bridge. If the corona branches reach the plane, the development of a positive leader begins without a preceding stepped leader.

Thus, at $A = 100 \div 50$ kV/ μ sec, breakdown passes through the following stages: 1) primary and repeated i.c.; 2) stepped leader; 3) negative leader; 4) space leader, its bridging with the negative leader; 5) breakdown under a standard wave.

We note that a velocity of $5 \cdot 10^6$ cm/sec is critical for the stepped leader; below it, apparently, it cannot develop. The formation of space leaders (several of them may develop in one channel of a stepped leader) is usually observed after 10 μ sec from the moment of occurrence of the first discharge processes. The space leader, merging with the negative leader, leads as it were to a sharp decrease in the length of the unbroken gap, and therefore on the oblique wave a decrease in

U_p is recorded.

At $A = 40 \div 3$ kV/ μ sec, the discharge process begins with primary and repeated i.c. (Fig. 4 III). We note that the negative leader degenerates (Fig. 4 III–3) into the form of a push-shaped leader, from the end of which a pulsed corona arises. This process repeats with some pauses, and each time the length of the leader channel and of the i.c. branches increases. A phenomenon of this kind was observed earlier by Walter (7). The cause of such development of the process is probably a space leader that merges with the channel from the rod. A rapid increase in the potential of the space leader occurs, owing to which an i.c. is formed from its lower head. For $A = 40 \div 30$ kV/ μ sec, the effective velocity of advance of the boundary of the i.c. branches is equal to $(3 \div 5) \cdot 10^6$ cm/sec, while the effective propagation velocity of the push-shaped leader is of the order of $1.0 \cdot 10^6$ cm/sec. The elongation of the negative leader ultimately leads to breakdown of the type occurring under a standard wave. Thus, at $A = 40 \div 3$ kV/ μ sec, the development of breakdown in the right-hand part of the U-shaped characteristic passes through the following stages: 1) primary and repeated i.c.; 2) push-shaped leader; 3) breakdown under a standard wave. Before the transition to the noted type of breakdown, rather intense i.c. flashes develop, increasing the space charge at the head of the channel, which retards the development of the negative leader; here U_p is larger than for the scheme of Fig. 4 II. This explains the rise of the branch of U_p to the right of the minimum.

Summarizing the development of the negative spark, one may single out the main elements of breakdown preparation: 1) pulsed corona (initial and repeated); 2) stepped spark leader; 3) negative leader and push-shaped leader; 4) space leader; 5) positive leader; 6) final jump; 7) main channel.

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