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AN INVESTIGATION OF A LONG SLIDING SPARK

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The breakdown characteristics of sliding sparks up to 2.5 m in length of different gases are investigated at various pressures. Investigations of sliding sparks in air at atmospheric pressure have been described in [1, 2]. The investigations in this paper were conducted in argon, neon, helium, and air at pressures from 10 to 1600 mm Hg. Creepage arose on the surface of the dielectric film with which the metal tube attached to one of the electrodes (the so-called "initiator") was wrapped. The diameter of the initiator was equal to 40 mm. The film thickness was 0.4-4 mm. The length of the discharge gap was varied from 0.25 to 2.5 m. The discharge occurred in a dielectric chamber 450 mm in diameter which was evacuated and then filled with the different gases. A cable transformer [1, 2] served as the voltage source. The voltage in the secondary winding had the shape of a decaying cosine with a frequency from 30 to 120 kHz. The logarithmic damping constant was equal to 10^{-2}.

Experimental Results. The value of the breakdown voltage U_{br} was investigated in all the experiments. This value was defined as the smallest amplitude at which the sliding spark spans the discharge gap.

The effect of the thickness of the dielectric film Δ(mm) can be expressed in terms of the effect of the specific capacitance of the film $C_{sp} = 0.88\ \varepsilon/\Delta$, upon which the breakdown voltage depends uniquely.

The $U_{br}(C_{sp})$ relation for argon, neon, helium, and air plotted for a gap length of $l = 1$ m at atmospheric pressure is given in Fig. 1 (curves 1-4, respectively). It is evident that as C_{sp} increases U_{br} falls off sharply at first. But starting from C_{sp} of 2-5 pF/cm², the variation of U_{br} becomes mild. It is possible to explain this physically by the fact that initially the increase of C_{sp} results in an increase of the capacitive current, and consequently of the total current through the incomplete discharge channel. The current increase leads to a decrease in the resistance of the channel and an effective transfer of the potential of the high-voltage electrode (from which the creepage develops) to the tip of the incomplete leading channel. This potential provides for the occurrence of ionization processes at the tip and the development of a leader. At a sufficiently large value of C_{sp} the increase in the potential at the tip undergoes saturation.

It is also evident from the data of Fig. 1 that the relation of the breakdown voltages for different gases depends weakly on the quantity C_{sp} for sufficiently large values of C_{sp}. One can explain this situation also by the decisive effect of ionization processes at the tip of the incomplete channel of the leader. The processes are determined mainly by the area in front of the tip in which multiplication of cascades and streamers occurs. The dependence of U_{br} on the length of the discharge gap l is given in Fig. 2 for argon (1 and 1'), neon (2 and 2'), and helium (3 and 3') with C_{sp} equal to 1.6 (curves 1-3) and 3.0 pF/cm² (curves 1'-3').

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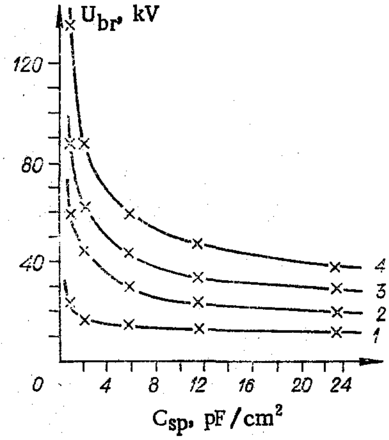

Fig. 1

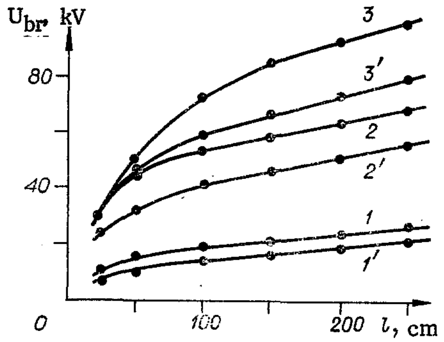

Fig. 2

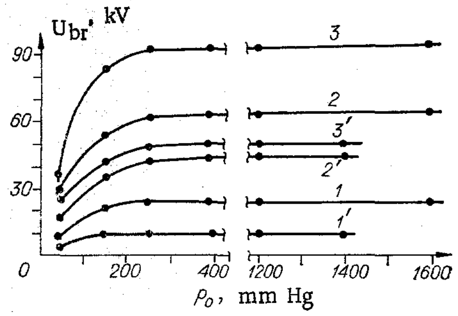

Fig. 3

As has been noted earlier, a bend is observed in the $U_{br}(l)$ curve for the case of air [2]. For values of $l \geq l_{cr}$ the voltage increases practically linearly with l (the field strength in the segment of the channel from l_{cr} to l remains unchanged). It turned out that the point of inflection (l_{cr}, U_{cr}) is determined (at least in the region investigated) only by the value of C_{sp} and the kind of gas (at an initial pressure $p \geqslant 200$ mm Hg) and does not depend on p:

$$U_{cr} = AC_{sp}^{-0.5}, \text{кВ}; \quad l_{cr} = BC_{sp}^{-0.5}, \text{m}.$$

The constants A = 80 and B = 1.15 for helium, A = 54 and B = 0.75 for neon, and A = 17.2 and B = 0.75 for argon. The values of the constants of the field strengths in the region above l_{cr} are as follows: E_{br} = 14.5 kV/m for helium, 8.3 kV/m for neon, and 4.5 kV/m for argon. For $l \geqslant l_{cr}$ one can determine the breakdown voltage from the formula

$$U_{br} = 1{,}1[U_{cr} + E_{br}(l - l_{cr})], \text{kV} . \tag{1}$$

The values of U_{cr}, l_{cr}, and E_{br} given permit determining U_{br} from (1) with an error of about 10%. The dependence of U_{br} on the gas pressure is shown in Fig. 3. In contrast to Paschen's curves, the pressure has no effect on U_{br} over a wide range. Curves 1 and 1' are obtained for argon, 2 and 2' for neon, and 3 and 3' for helium; curves 1-3 refer to the case of a film thickness $\Delta = 2$ mm ($C_{sp} = 1.6$ pF/cm²) with a length $l = 2$ m, and curves 1'-3' refer to $\Delta = 0.5$ mm ($C_{sp} = 3$ pF/cm²; with a length of 0.5 m.

The fact that the gas pressure has no effect over wide limits on the development of the leader indicates that in the case under discussion the value of E/p (E is the field strength at the tip), which determines the intensity of the ionization processes at a given point in the gas, has no appreciable effect on the development of the leader. At the same time an effect of C_{sp} is exhibited upon a change in the pressure p (see Fig. 3). As a result one can conclude that the development of the leader is determined mainly by the value of the total current flowing into its tip, and this quantity is determined in turn by the area above which ionization processes are occurring. The intensity of these processes

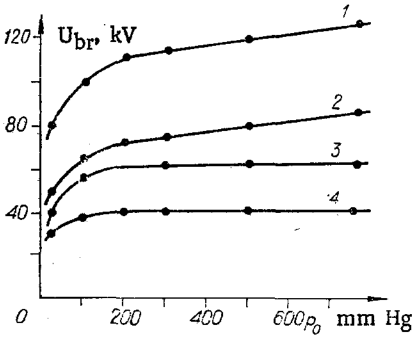

Fig. 4

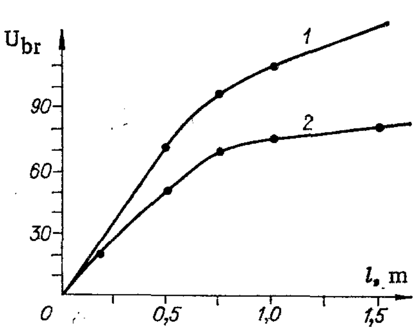

Fig. 5

remains practically constant, since there exists in the region of the electric field at the tip a large overvoltage, and the variation of E/p upon a variation of p does not increase the current supplying the tip of the leader under the conditions being considered, and the area with effective ionization is not altered (it is determined by the geometry of the original capacitor formed by a conductive rod lying above a conducting surface).

Development of the leader evidently occurs without significant overvoltages at the tip in the region of comparatively low pressures. Therefore, a variation of p leads to a variation of the intensity of the ionization processes and a variation of the surface of the "current collector" in front of the tip.

It is interesting that in an electrically negative gas such as air the effect of pressure is, in contrast to the inert gases, appreciable over the entire investigated range from 37 to 800 mm Hg (Fig. 4) if $l > l_{cr}$ (curves 1 and 2 refer to a discharge gap length $l = 1.9$ m with $l_{cr} = 1.08$ m and 0.79 m, respectively). For a small discharge gap length $l < l_{cr}$ (curves 3 and 4 are obtained for $l = 0.35$ m and the same values of l_{cr}) the effect of pressure decreases.

We note that in the case of air the increase in the breakdown voltage with increasing pressure occurs linearly for $l > l_{cr}$ with a constant 0.014 kV/mm Hg for $p \geq 200$ mm Hg. In order to explain the data of Fig. 4, which show a different effect of p for short $l < l_{cr}$ and long $l \geqslant l_{cr}$ gaps, one should include the dynamics of the development of the sliding spark [1].

The investigations have shown that breakdown in argon differs from breakdown in the other gases in the rapid rate of development of the leader channel in the discharge gap; breakdown in all the cases investigated occurred during the voltage rise time.

In the case of helium, neon, and air the average rate of development of the leader channel is less than in argon, and for $l \geqslant l_{cr}$ development of the breakdown encompasses a region of voltage which varies abruptly in time. The development occurs nonuniformly [1]. Characteristic halts and even "extinctions" of the channel occur in the development which are determined both by the absolute value of the instantaneous voltage and by its time derivative. The variety of breakdown characteristics of a sliding spark encountered in the literature [3-8] is explained by this situation.

One can conclude from an analysis of the temporal structure of the development of a sliding spark that the characteristic of the breakdown which depends on the gap length (on the breakdown time) is characterized by a region of breakdown voltages lying between two limiting cases (Fig. 5, air, 1 atm). Curve 1 refers to the case of breakdown with a single ("nondecaying") leader which moves from one electrode to the other without interruption. Curve 2, which lies at lower values of the breakdown voltages, corresponds to the development of a leader with interruptions. The number of such interruptions exceeded ten under our conditions. In this case the breakdown occurs at the minimum value of the voltage.

In the first case the average velocity of the leader does not differ too much from the instantaneous value and is $(5-8) \cdot 10^8$ cm/sec, and in the second case it lies one to two orders of magnitude lower (from $5 \cdot 10^6$ to $7 \cdot 10^7$ cm/sec). Thus, Eq. (1) determines the lower breakdown characteristic in the case of helium, neon, and air and the upper one in the case of argon.

We note that one should use the upper breakdown characteristic in order to obtain a dense system of parallel discharges.

Returning to the data of Fig. 4, one can assume that the decrease in the effect of pressure upon a decrease in the discharge gap length is associated with a transition from a multistage breakdown to a single-shot breakdown. In the case of a single-shot breakdown in air the field surge at the tip is rather large, and the variation of E/p upon a variation of p has no effect on the process of development of the breakdown. In helium and neon no such effect is observed in connection with multistage breakdown.

The analysis of all the data presented from the point of view of elementary processes permits explaining the distinctive features of the breakdown in argon by the presence of more powerful ionizing radiation than in helium and neon. The distinctive features of an air breakdown are related to its electrically negative nature and large heat capacity, which results in a lower (in comparison with the inert gases) temperature and conductivity.

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