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Abstract

Full Text

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On the Internal Instability of an Arc with a Cold Cathode

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When studying the process of establishment of an arc and its stability in one or another final state, until quite recently it was considered permissible to confine oneself to the purely phenomenological formulation of the problem proposed by Kaufmann more than 50 years ago ($^{1-5}$). In this approach, the individual properties of the arc were reduced to a falling volt-ampere characteristic, while its final state was regarded essentially as stable*. In this form the theory of arc stability cannot serve even as a first approximation to reality. As observations show, the extensive class of arcs with metallic cathodes is characterized by internal instability not only in transient regimes, but also in any final state. The phenomena of internal instability of the arc are found under any conditions of the external circuit, in particular for its parameters that exclude the possibility of growth of small current fluctuations and the generation of oscillations in a system with negative resistance (a strongly damped, aperiodic circuit).

Fig. 1. Schematic representation of the division of the cathode spot on metallic cathodes during time scanning of the process

The natural criterion for the stability of any stationary** discharge is its ability to remain for an unlimited time at unchanged values of current or voltage. Below, a number of features of an arc with a cold cathode that are incompatible with this criterion are indicated.

Among the obvious manifestations of arc instability one should include its spontaneous extinctions in the region of small currents. For an arc with a mercury cathode this region extends from 0.1 a to 7–10 a, and with increasing current the probability of extinction gradually decreases ($^{6-8}$). At currents above 7 a, extinctions are already so rare that obtaining information about them becomes difficult (^{8}). On this basis it has hitherto been customary to attribute instability phenomena exclusively to the indicated intermediate range of currents (^{6}). Such an interpretation of the phenomena, however, contradicts the facts. That instability is inherent in the very nature of the arc is shown by the processes, characteristic of metallic arcs, of continuous division and disintegration of the cathode spot (9), represented schematically in Fig. 1. In it each branching of a line represents the division of the spot into two parts. One of the newly formed spots soon disintegrates, having passed through a life cycle of one or another duration τ. The other spot, which it is convenient to call the "carrier of the relay," maintains the arc until a new act of division. The intervals times t between successive acts of division are distributed over a narrow range of values. For a mercury cathode, the mean values of both intervals are, in order of magnitude, 10^{-5} sec. Phenomena on many other metals have the same character. The data on the systematic division and disintegration of spots can be interpreted only as evidence of the instability of the cathode spot on a cold cathode at low pressures. It is quite natural to associate extinction of the arc with this instability of the spot, but then it is necessary to explain the discrepancy between the magnitude τ and the mean duration of arc burning.

Analysis of the phenomena of arc extinction and of the behavior of the spot at small and large currents leads to the conclusion that the process of maintaining the arc is a continuous alternation of cycles of decay and cycles of restoration of the spot by voltage pulses, in whose formation the inductance always present in the circuit participates. Indeed, any decrease in the current within a disintegrating autonomous spot is accompanied by an increase in the voltage at the electrodes. If there are also other emission centers on the cathode, this rise is easily compensated by an increase in their emission current and, consequently, cannot prevent the disintegration that has begun in the given spot. The role of the voltage pulse in this case is reduced to a redistribution of current among the individual spots and to regulation of their number, with the deviation of the voltage from the mean being small. When only one single spot "carrying the baton" remains on the cathode, the voltage increases until a new influx of its vital activity occurs, if this is possible under the existing conditions. As a result of the restorative action of a series of pulses, the duration of arc burning in either case proves to be sharply increased in comparison with τ. The reliability of this process is determined by its automatic character and depends on the current, which also explains the relative longevity of the arc and the decrease in the probability of its extinction with increasing current. It is noteworthy that the duration of arc burning becomes very large precisely at currents at which the discharge is distributed, on average, among several cathode spots. Restoration of the arc under such conditions proceeds by the type of redistribution of current among the individual spots, which is associated with a smaller probability of extinction.

The conclusions drawn concerning the instability of the arc and the mechanism

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* The oscillatory regime of the arc predicted by the theory under certain particular conditions of the external circuit can easily be eliminated by an appropriate choice of the circuit parameters.

** That is, of a discharge maintained by a constant-voltage source.

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

of its restoration were confirmed by a number of experiments in which an accumulator battery served as the voltage source (130 V). By reducing the distance between the cathode and the anode to 0.3–0.4 cm, the desired type of oscillations with cathode localization was isolated from the diverse oscillatory processes of the arc (^{10}). Of particular interest was the study of oscillations under conditions of an arc with a fixed spot, since in this case there is assurance that the nature of the oscillations is not connected with chaotic displacement of the spot over the cathode and with the accompanying phenomena. The spot was fixed at the wetting boundary of a molybdenum strip shaped as a triangle, one of whose vertices projected above the surface of the mercury. Opposite the fixer, in the anode, there was a hole about 7 mm in diameter, through which the light flux from the spot reached a photomultiplier with an antimony-cesium cathode. With a two-beam oscillograph, simultaneous observations were made of the oscillations of the voltage and of the light flux. In the path of the latter an additional lens was placed, by means of which the image of the cathode was projected in the plane of the photomultiplier diaphragm, making it possible to study separately the light flux coming from the cathode spot and from the remaining parts of the discharge. Thus it was established that the principal source of the light flux and of its oscillations was the cathode spot. One of the typical oscillograms of arc oscillations with a fixed spot at a current of 1.4 A and aperiodic conditions of the discharge circuit is shown in Fig. 2a. In it the upper trace indicates the change in the anode voltage, and the lower one the change in the light flux of the cathode spot. One trace rep–

Fig. 2. Oscillograms of oscillations of the voltage (U) of a short arc and of the luminous flux (Φ) of the cathode spot; **a, b, c** –stationary spot, scale 0.5 V, 10^{-4} sec.; **d, e** –moving spot, scale 1 V, 10^{-4} sec.

Fig. 3. Spectrograms of the glow of the cathode region of a mercury arc with different amounts of Ne: **a** –20 mm Hg, **b** –7 mm, **c** –0.5 mm

Fig. 3

constitutes almost a mirror image of the other, which indicates synchronism and, at the same time, the cathodic origin of the oscillations. The amplitude of the voltage oscillations is, in order of magnitude, 0.1 V, with an average arc-burning voltage of 7.5 V. From the appearance of the oscillograms it could be assumed that the oscillations are the result of the superposition of pulses emitted by many emission centers. Since, according to Tonks'data (^{11}), each such center carries on average a current of about 0.2 A, there was hope of resolving the oscillations into separate pulses by reducing the current to tenths of an ampere. The triggered sweep of the oscilloscope was started in synchronism with a sudden decrease of the current, with one or another delay. Owing to this, it became possible to study the behavior of the spot from the moment of current reduction until interruption of the arc. Figure 2b presents one of the oscillograms obtained when the current was reduced to 0.27 A. In it the coordinated oscillations of voltage and luminous flux do indeed take the form of single pulses, or of pulses arranged in groups. The amplitude of the voltage pulses ranges from 0.01 to 0.6 V. The duration of single pulses, allowing for the correction for amplifier distortion, is no more than 10^{-7} s. The arc-extinction time proves to be of the same order. Most often on the oscillograms, pulses of large amplitude are arranged in groups. As the current is reduced from 1 to 0.08 A, the amplitude of the pulses in the groups increases, but at the same time completely smooth portions of the oscillograms appear, with a duration of up to 10^{-5} s and somewhat more (Fig. 2c). Usually, arc interruption occurs at one of the groups of pulses of large amplitude, whence it follows that the appearance of a group always corresponds to a critical state of the cathode spot, which may be resolved by either restoration or extinction of the arc, depending on the coincidence of random circumstances. At currents below 0.07 A the cathode spot can no longer exist.

Much of what has been said may be applied to an arc with a freely running spot, although in this case the amplitude of the oscillations proves to be several times larger. The grouping of pulses and the interruption of the arc at one of the groups under the conditions of an arc with a running spot are illustrated by the voltage oscillograms in Figs. 2d, e. They reveal still another feature of the oscillations: against a background of pulses with an amplitude of about 0.5 V, following one another with a period of $\sim 3 \cdot 10^{-6}$ s, groups of pulses with an amplitude of 5–6 V and intervals of the order of 10^{-4} s also appear periodically. The double periodicity in the behavior of the spot may serve as an expression of instability of two types—electrodynamic and energetic—which should be connected with the sharp concentration of current within the cathode spot. The amplitude of the pulses of the high-voltage group is approximately equal to the difference between the ionization potential (10.39 V) and the excitation potential (4.89 V) of mercury vapor. This circumstance suggests that, under the critical conditions of existence of the spot, the efficiency of stepwise ionization in the region of negative glow drops sharply, as a result of which the cathode fall increases until the electrons acquire energy sufficient for direct ionization of mercury vapor. One of the causes of this may be a decrease in the density of neutral particles in the region of negative glow as a result of cooling, or explosive phenomena of mercury overheating in the region of the spot.

The proposed interpretation of the mechanism of arc restoration can be confirmed by means of a simple experiment. If neon is added to a tube with a mercury cathode at a pressure from 0.1 to 30 mm Hg, a red flickering glow appears in the cathode region of the arc, the intensity of which increases as the current is decreased. The appearance of Ne glow proves that the mean energy of the electrons at times approaches 16.8 eV. With the aid of a two-beam oscilloscope and a photomultiplier with an oxygen-cesium cathode, additionally provided with a red light filter, it was established that Ne glow pulses appear simultaneously with voltage pulses, if the amplitude of the latter reaches 5–6 V (oscill-

logram 2 e). By moving the image of the arc in the plane of the photomultiplier diaphragm, it is easy to verify that the source of the fast electrons is the cathode fall. This conclusion is confirmed by the nonuniform distribution of optical density along the Ne lines in the spectrograms of Fig. 3, taken at increasing inert-gas pressures. When photographing the spectrum, a reduced inverted image of the arc was focused in the plane of the spectrograph slit in such a way that the image of the cathode spot often intersected the slit in its upper part. The brightness of the Ne lines decreases with distance from the cathode spot the more sharply, the higher the Ne pressure. This experiment proves the cathodic origin of the fast electrons and, at the same time, the instability of the cathode fall itself.

The data presented on the voltage oscillations of a short arc confirm the conclusions drawn in the work concerning the internal instability of an arc with a cold cathode. Neither in amplitude nor in form can these oscillations be identified with the statistical current fluctuations inherent in every discharge. Oscillations are observed at any, including very large, discharge currents; it follows from this that the instability is not an exceptional property of the arc in the region of small currents. The physical basis for such a conclusion is that, as the current increases, the spot is merely fragmented into an ever greater number of parts, each of which remains unstable as before. With increasing current, however, the conditions for restriking the arc are facilitated, as a result of which the amplitude of the voltage pulses decreases. The result of the reduction in the pulses is the so-called falling characteristic of the short arc, i.e., a decrease in the mean values of the arc burning voltage with increasing current.

The cathode-spot instability considered here provides a good explanation of the high mobility of the spot and its tendency toward continuous division.

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Note: Figure translations are in progress. See original paper for figures.