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Abstract

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I. G. Kesaev

On the Causes of the Ordered Motion of the Cathode Spot of an Electric Arc in a Magnetic Field

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The ability of the cathode spot to undergo ordered motion in the presence of a magnetic field has long attracted the attention of physicists because of the unusual direction of the motion at low ambient pressures ([1]-[10]). In a uniform field this direction proves to be diametrically opposite to that in which charges should be deflected by the electromagnetic force. This type of motion has been called "retrograde."

Many years of study of "retrograde" motion ([3]-[9]) have not clarified the question of the mechanism of the ordered motion of the spot. It is a serious omission that, in solving this question, until very recently no account was taken of the intrinsic magnetic field of the cathode parts of the arc, whose strength near the boundaries of the spot, by approximate estimate, may reach 600 oersteds. As a result of the superposition of the external field and the arc' s own field, a sharp asymmetry inevitably arises in the distribution of the field at the boundaries of the spot. As is shown below, asymmetry of this kind may be the dominant cause of the motion of the cathode spot at low pressures.

If there is an asymmetry of the conditions near the boundaries of the cathode spot, one should allow for the possibility of displacement of the spot in the direction in which the emission conditions prove to be more favorable. To clarify the role of magnetic-field asymmetry in the motion of the spot, it is first necessary to obtain an answer to two questions:

1. Does the magnetic field influence the operating conditions of the spot?
2. Is there a correspondence between the direction of motion and the direction in which a change in the resultant magnetic field in the region of the spot may be regarded as most favorable in terms of its action on the arc?

As experience shows, the application of a magnetic field of any orientation leads to a noticeable increase in the stability of the cathode spot of a low-pressure mercury arc, and the stabilizing action of the field increases with increasing field strength. This action is manifested in the fact that, under conditions of an unstable arc obtained near the critical values of the arc current (0.5–3 A),

Fig. 1. Graphical construction for the addition of the arc’ s own magnetic field H_i and the external field with components H_x and H_y

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the application of a field causes stabilization of the cathode fall and an increase in the average duration of arc burning. In view of this, asymmetry in the field distribution at the boundaries of the cathode spot is capable of causing a displacement of the spot as a result of the formation of new, more stable emission centers near one of its boundaries. The displacement of the spot caused by the asymmetry of the field must be directed toward its increase. The same conclusion is reached by an analysis of the asymmetry in the distribution of the concentration of charged particles around the boundaries of the spot, formed as a result of the electron-optical action of the magnetic field. The principal feature of the concentration distribution is that the maximum of the field must correspond to the maximum of concentration. A noticeable asymmetry in the concentration distribution may, however, arise

only at low ambient pressures, at which the mean free path of electrons λ remains greater than the mean Larmor radius R.

Thus, in the indicated pressure range the direction of motion of the cathode spot on the mercury cathode must coincide with the direction of the steepest increase of the total magnetic field near the boundaries of the spot. As follows from what is developed below, application of the stated principle of the field maximum, without any additional assumptions about the mechanism and shape of the spot, makes it possible to predict the direction of motion in the general case of a nonuniform field. In this case the field strength of the current i, moving together with the spot, can be specified by the simple relation

$$H_i = \frac{0.2i}{r}, \tag{1}$$

which is valid for any shape of the spot at distances r exceeding its dimensions.

In Fig. 1 the field of the arc on a circle of radius r, drawn from the center of the cathode spot O, is represented by a vector directed tangentially to the circle. Owing to the symmetry of the arc field with respect to the spot, this field by itself cannot cause a selective displacement of the spot in any one direction φ. The asymmetry necessary for this arises as a result of the superposition of the external field H. For the subsequent conclusions, the case of a strong field is of interest, in which the random motion is reduced to a minimum and the trajectory of the spot becomes regular. In the case of a strong field, the directions φ_m in which the total field on the circle reaches extreme values can be determined with sufficient accuracy from the equation

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$$\operatorname{tg}\varphi_m = \frac{\dfrac{\partial H}{\partial x} - \dfrac{H_y}{H}\dfrac{0.2i}{r^2}}{\dfrac{\partial H}{\partial y} + \dfrac{H_x}{H}\dfrac{0.2i}{r^2}}. \tag{2}$$

The axes x and y are located in the plane of the cathode, and the angle φ is measured from the positive direction of the y-axis toward positive x. The components of the external field H_x and H_y are considered positive if the corresponding vectors are directed in the positive direction of the axes. For each value of the fraction on the right-hand side of the equality there correspond two directions φ_m, of which one is the direction of the maximum and the other that of the minimum of the field. Since they are diametrically opposite, the direction of the maximum is also the direction of motion of the spot, if r denotes the effective radius of interaction of the cathode spot with the magnetic field. In the sense of the problem posed, the quantity r must somewhat exceed the actual dimensions of the spot, since the direction of motion depends on the distribution of the field in the vicinity of the spot. If the coordinate axes are arranged so that the denominator on the right-hand side of the equality remains positive, then acute angles will correspond to the field maximum, and from (2) one may pass to the differential equation of the trajectory by replacing $\operatorname{tg}\varphi_m$ with the derivative $\dfrac{dx}{dy}$. In a uniform field,

$$\operatorname{tg}\varphi_m = -\frac{H_y}{H_x} = -\operatorname{tg}\alpha,$$

a, consequently, the spot must move at a right angle to the direction of the tangential component of the field H, since the angles φ and α are measured from mutually perpendicular axes. It is easy to verify that the direction of this motion is opposite to the direction of deflection of the electrons emitted by the cathode in the field H, i.e., the motion is of the "retrograde" type. In a nonuniform field $\operatorname{tg}\varphi \neq -\operatorname{tg}\alpha$, and the direction of motion must be determined by the more complicated rule (2).

The equation of the trajectory of the cathode spot takes on a simple form in the case of a field depending only on the coordinates x and z, with a tangential component directed along the x-axis:

$$\frac{dx}{dy} = \frac{r^2}{0.2i}\,\frac{H}{\bar{H}}\cdot\frac{dH}{dx}. \tag{3}$$

A field of this kind is obtained above the pole pieces of an electromagnet separated by a gap in the form of a parallel slit situated along the y-axis. A

Fig. 2. Arrangement of the pole pieces and trajectory of the cathode spot

Figure 2: Fig. 2. Arrangement of the pole pieces and trajectory of the cathode spot

characteristic feature of the trajectory is that the angle of inclination of the tangent to the direction of "retrograde" motion, coinciding with the direction of the y-axis, must be approximately proportional to the nonuniformity of the field. This property of the trajectory is readily understood from the relation that exists between the "retrograde" motion of the spot and its displacement toward increasing field. Both of these motions are caused by a common cause —the asymmetry of the field in the region of the spot. The asymmetry of the superposition of the external and self-fields gives rise to the "retrograde" motion, whereas the asymmetry of the external field by itself serves as the cause of the deflection of the spot along the x-axis.

Fig. 2. Arrangement of the pole pieces and trajectory of the cathode spot

The indicated property of the trajectory was confirmed experimentally. In the initial experiments the spot moved on a homogeneous mercury cathode in the field of an electromagnet, the pole pieces of which were located 0.6 cm below the level of the mercury. Subsequently, in order to eliminate distortions associated with the excitation of surface mercury waves, the mercury cathode was replaced by a smooth copper plate coated with a thin layer of mercury. The plate was mounted above the pole pieces, the gap between which had the form of a slit 1 cm wide and 6 cm long. The equilibrium pressure of mercury vapor in the volume corresponded to a temperature of 20–22°.

The usual path of the spot is shown schematically in Fig. 2. From the place of its origin O, the spot moved in the direction of the axis of symmetry of the field, continuously approaching it. Having reached the boundary of the cathode at point P, the spot went around the cathode along the right or left semicircle until it intersected the axis of symmetry at point Q and rushed along this axis, making it clearly visible in the photographs.

Figure 3 gives a photograph (3×) showing the trajectory of the spot at a current of 3 A and a field strength on the axis of symmetry of the field $H_0 = 1300$ oersted. As processing of many similar photographs showed, within distances $x = 0.7$ cm from the axis of symmetry of the field, the trajectory y of the spot can be expressed by the simple equation:

$$\ln \frac{x_0}{x} = Ay. \tag{4}$$

Within these limits, the field distribution used in the experiments can be approximated by the expressions

Fig. 3. Photograph of the trajectory of the cathode spot in a nonuniform field (3×)

Figure 3: Fig. 3. Photograph of the trajectory of the cathode spot in a nonuniform field (3×)

$$H = H_0(1 - ax^2),$$

$$H_x = H_0(1 - bx^2)$$

for the values of the constants $a = 0.28$ cm^{-2} and $b = 0.76$ cm^{-2}, and equation (4) represents, with sufficient accuracy, the trajectory obtained from the solution of differential equation (3). The constant A turns out to be related to r by the relation:

$$A = \frac{2.8H_0}{i} r^2.$$

The numerical value of A was found to be 1.1 cm^{-1} for a current of 3 A and 1.65 cm^{-1} for a current of 15 A, whence the effective radius r is found to have, respectively, the values $3.3 \cdot 10^{-2}$ cm and $9 \cdot 10^{-2}$ cm.

Fig. 3. Photograph of the trajectory of the cathode spot in a nonuniform field (3×)

The actual dimensions of the spot at the indicated current values, according to Froome' s data [11], vary within the limits from $0.3 \cdot 10^{-2}$ cm to $1.5 \cdot 10^{-2}$ cm.

The agreement between the form of the theoretical and actual trajectory of the spot in a nonuniform field, as well as the reasonable order of magnitude of the radius r, determined by comparing theory and experiment, indicates the correctness of the assumptions made about the dominant role of the asymmetry of the magnetic field in the region of the cathode spot in the mechanism of the ordered motion of the spot at low pressures.

All-Union Electrotechnical Institute
named after V. I. Lenin

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