Experimental Study of Cathode Spot Motion and Burning Voltage of Low-Current Vacuum Arc in Magnetic Field

Konstantin K. Zabello, Yury A. Barinov, Alexey M. Chaly, Alexander A. Logatchev, and Sergey M. Shkol'nik

***Abstract*—This experimental study dealt with cathode spot (CS) otion and the burning voltage of a low-current vacuum arc with ectrodes of HCOF Cu and with a composition of CuCr30, subcted to a magnetic field. Arcs with current of $I \approx 30$ A burned axial and transverse fields as well as with the induction vector inined at an angle $5^\circ < \varphi < 65^\circ$ to the cathode surface. Butted-end lectrodes were used with diameter 30 mm and gap $h = 4$ mm. he field components, axial B_n and transverse B_t, were varied inependently over a wide range. The superposition of a transverse agnetic field on the arc was found to considerably increase both e constant component and noise level of the voltage U. If this arc also superposed with an axial field, both the constant component nd noise level decrease. With growing B_n, the dependencies of the (B_n) at different values of B_t converge to a single curve that is ypically V-shaped. This is similar to the dependence of the voltage cross a high-current vacuum arc with fixed current in an external xial magnetic field on the magnetic field induction. The velocity f the retrograde CS motion grows approximately in proportion o the growth of the transverse field. The proportionality factor is $\sim 60\ \mathrm{m/(s \cdot T)}$ for Cu and $\sim 200\ \mathrm{m/(s \cdot T)}$ for CuCr. Increase f the axial field causes a slight reduction in the magnitude of the elocity vector and its rotation with respect to the retrograde diection through an angle θ, its value being proportional to the field nclination angle φ. The results obtained were compared with the ata in references.**

***Index Terms*—Cathode spot motion in magnetic field, low current vacuum arc.**

I. INTRODUCTION

SOME integral characteristics of a low-current arc in vacuum are yet to be studied in detail, notwithstanding the hundred years' history of research into this kind of arc discharge. Among numerous works, whose results are summarized in a number of monographs and reviews, in particular [1]–[4], we note those where the study concerned the results of the action of a magnetic field on the burning voltage of an arc on a cold cathode and the motion of its cathode attachment, the so called "cathode spot" (CS).

The vast majority of this research was performed on rather short (several millimeter) arcs superposed with a transverse (tangential) magnetic field, i.e., one with the induction vector B_t parallel to the plane of the cathode. A CS was found to move under the action of B_t in the direction opposite to that of the Ampere force acting upon the current passing through the spot. For this reason, the motion of a CS under the action of the transverse field was termed "anti-Ampere" or "retrograde." The prevailing point of view is that velocity V of the retrograde motion is proportional to the field induction: $V = kB_t$. The proportionality factor k depends on the material of the cathode, the state of its surface, and the arc length h.

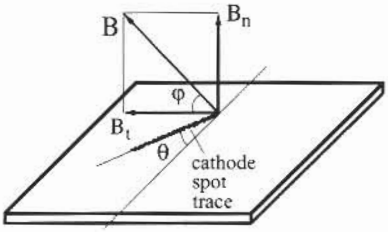

Fig. 1. Schematic of the geometry of the experiment.

The values of k reported by different authors vary greatly. Differences in the order of magnitude of k are explainable by the diversity of vacuum conditions. CSs that burn on contaminated surfaces in low vacuum are referred to as spots of the first type and move much faster than the ones that burn on clean surfaces in high vacuum that are referred to as spots of the second type [2]. Still, even in experiments with spots of the second type significantly different values of k were obtained [5]. Note also that most of the research was performed on cathodes made of pure metals. Investigations on composite materials such as CuCr and other materials used presently in vacuum switchgear are few in number [6].

Considerably less studied are phenomena when a low-current arc is superposed with an axial magnetic field, i.e., one with the induction vector B_n normal to the cathode surface, as well as with the induction field vector inclined at an angle $\varphi = \arctan(B_n/B_t)$ with respect to the cathode surface, that is, when the field has both components, B_t and B_n. It was observed in [7] that in the presence of the B_n component, the direction of CS motion makes an angle θ with the anti-Ampere, retrograde one (defined by the B_t component) (Fig. 1). The value of θ depends on the ratio of B_n and B_t, i.e., on the angle φ; namely, $\theta \approx \varphi$. The experiments were performed under poor vacuum conditions. For high vacuum and clean surfaces, the work [8] reports a different result: $\theta \approx 0.5\varphi$. The measurements in this work were conducted only on Mo and C cathodes in a limited number of modes. The spread in values is substantial. Therefore, the development of the study is of indubitable interest.

Manuscript received February 22, 2005; revised July 1, 2005.

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Digital Object Identifier 10.1109/TPS.2005.856515

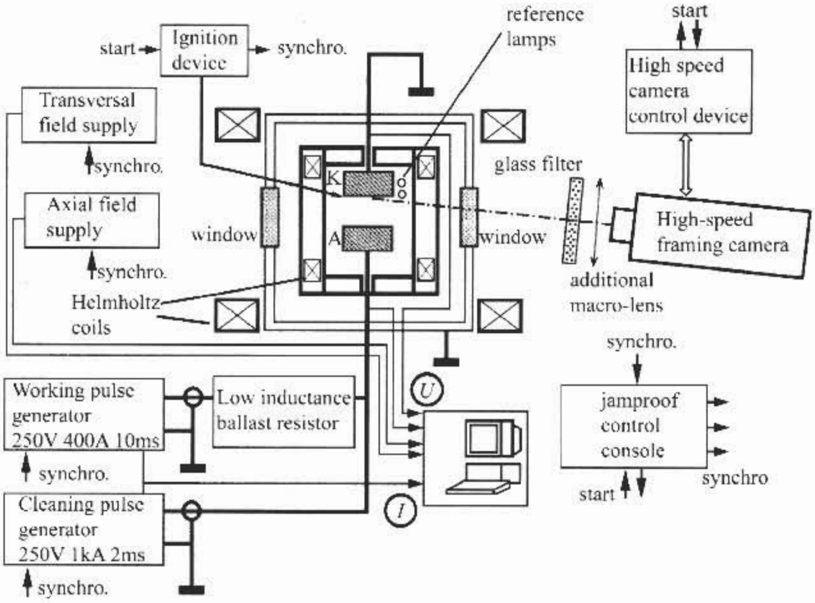

Fig. 2. Block diagram of the experimental setup.

Quantitative data on the dependence of the voltage U across a low-current arc on magnetic field are also rather scanty. The voltages across low current arcs on cathodes of some pure metals stabilized by axial magnetic fields are given in [9] and [10]. Data on arcs on composite materials can be found in [6]. Voltages across the arc on a Cu cathode subjected to a transverse magnetic field can be found in [11]. Neither reference has data on the burning voltage across an arc subjected to a magnetic field inclined with respect to the cathode surface.

The objective of the work we started is the experimental study of a low-current arc in magnetic fields with wide-ranging induction and field alignment at different currents and cathode materials, composite materials included. This kind of data, in addition to a purely physical interest, is necessary for gaining insight into the processes of high-current arcs stabilized with axial magnetic fields, their active investigation being undertaken for the development of vacuum switchgear. The present report gives results for arcs with Cu and CuCr30 composition cathodes at currents of $I \approx 30$ A and arc length $h = 4$ mm.

II. Experimental Setup and Measurement Technique

Fig. 2 gives the block diagram of the experimental setup. The measurements were performed in a stainless-steel vacuum chamber of volume ≈ 5 L under continuous pumping ($p \approx 10^{-4}$ Pa). Butted-end cylindrical electrodes with diameter $2R = 30$ mm and with contact plates of materials under study were used. Electrodes were fixed on bellows-type inlets that allowed control of the position of their planes with respect to the magnetic field (within an error of 2°) and adjustment of the interelectrode gap ($0 \leq h \leq 12$ mm).

The axial magnetic field was established with Helmholtz coils situated outside the chamber. The transverse field was established with Helmholtz coils placed in the chamber. The coils were wound onto a rigidly fixed fluoroplastic spool. Both pairs of coils produce a uniform magnetic field at the chamber center in a region of characteristic size greater than 40 mm. Each pair of coils was powered by separate current sources to permit independent adjustment of the current amplitude, the pulse duration, and the time delay of the current turn-on so that the discharge under study burned in a uniform quasi-stationary field for the duration of its existence (up to 10 ms). Oscillograms of the current of the coil power sources were recorded and stored in a computer.

The arc was powered by a thyristor-switchable artificial long line charged to 250 V and discharged through an adjustable low-inductance ballast into the arc. The source generated a square pulse of current $I \leq 400$ A with duration up to 10 ms. The present work used pulses of duration 2–4 ms. The source was connected to the chamber with a current-contact jaw designed to permit complete cancellation of the effect of the magnetic field of the reverse current on the arc. The discharge was initiated on the surface of the grounded cathode at a distance of several millimeters from the edge by breaking the contact in the auxiliary circuit with the help of a Mo initiation needle actuated by an induction-dynamic drive.

The work revealed a number of difficulties that required additional equipment to overcome. Namely, at $B_n = 0$, the burning stability of an arc of length $h = 4$ mm with current $I \approx 30$ A markedly weakens already at $B_t \sim 0.05$ T. At $B_t \geq 0.08$ T the arc practically extinguishes right after initiation. For this reason, while performing measurements in magnetic fields with $B_t/B_n \gg 1$, the above-described basic source that was only chargeable up to 250 V was changed for a higher-voltage one. It consisted of a capacitance $C = 300$ μF chargeable up to $U \leq 3$ kV and a variable ballast resistor. The drop in current during the measurement time (~ 1 ms) amounted here to less than 10%.

In the opposite case, while performing measurements in fields with $B_t/B_n \ll 1$, different difficulties were encountered. The arc (CS) failed to leave the site of initiation, "clinging" to the location of contact of the Mo initiation needle with the cathode. In such modes, a transistor pulse generator was connected in parallel to the basic supply through a diode to provide pulses of current $I \leq 500$ A with adjustable amplitude and duration

($0 < t < 2$ ms) and short leading and trailing edges. The current of the auxiliary high-current arc and its duration were chosen so that upon its extinction the low-current arc under study would burn at a distance of several millimeters from the site of initiation. The "breakaway" of the arc from the site of initiation was monitored using high-speed photography (see below).

Prior to starting the measurements, arc cleansing of the electrode surfaces was performed with a train of pulses from a different source with a current of $\sim$ 1 kA and duration 2 ms. Further on in the course of measurements, each working pulse was preceded by a cleaning pulse, the interval between the two pulses being $\sim$ 10 s.

The currents were recorded with a time quantization of 2 μs by oscilloscopes built into the power sources. The oscillograms were stored in a computer. Voltage was measured with an oscilloscope TDS 3012 supplied with differential input and was also stored in a computer.

The high-speed filming of the arc was performed using a high-speed photography (HSP) camera that allows capturing 60 sequential images during a filming session. The time of exposure was 25 μs per frame. The start of the filming could be delayed relative to the arc initiation by $0 < t < 2$ ms. Filming was done at an angle of $\sim$ 10°–15° with the plane of the cathode. The photography results were input into a computer using a film scanner HP S20 and processed with a program that allows finding the CS position on the cathode on each of 60 frames. The spot positions were defined relative to reference subminiature lamps (SMN 10-55-2). The lamps were rigidly fixed in the chamber and were turned on before the start of filming.

Control of the setup and synchronization of the power sources and recording equipment were carried out from a shielded control console.

The present paper describes the experiments performed with electrode contact plates of HCOF Cu and CuCr30 at currents of $28 < I < 32$ A and arc length $h = 4$ mm.

III. EXPERIMENTAL RESULTS

After several cycles of cleaning pulses, the magnetic-field free ($B = 0$ T) arc with a current $I \approx 30$ A burned steadily with relatively low level of noise during the entire pulse. No significant changes were observed in voltage with the growth of the charge that has passed through the cathode surface and, accordingly, the degree of the surface erosion. Upon superposing the transverse field, the arc became highly noisy and the constant component of voltage increased considerably. Figs. 3 and 4 give the results of measuring the dependence of the constant component of voltage U across an arc with CuCr and Cu cathodes at different values of B_t on B_n. The superposition of B_n is seen to produce a marked lowering of the voltage. With growing B_n, the dependence of $U(B_n)$ on different B_t converges to a single curve corresponding to $B_t = 0$ (Fig. 4). The curve monotonically increases, and hence, the curves at values of B_t other than zero are typically V-shaped. The convergence takes place at $B_n/B_t \approx 1.5$.

Fig. 5 gives an example of a CS image obtained with the HSP camera. The CS size full-width at half-maximum (FWHM) is 4 to 5 pixels (1 pixel ≈ 0.067 mm) as determined by the camera response function, exposure time, scanner sampling, and film grain size. The CS position was found by the maximum darkening of the photographic film to within 1–2 pixels. The same can be said of finding the coordinates of the reference lamps. (Sometimes, frames exhibit a division of the CS. In such cases, we chose the coordinates of the CS producing a stronger darkening of the negative.)

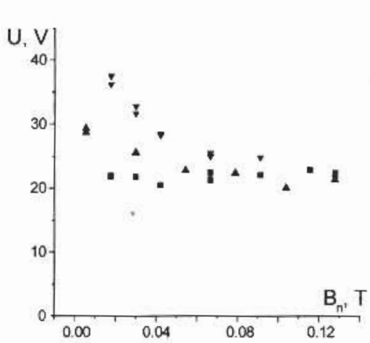

Fig. 3. Dependence of arc voltage on CuCr cathode at different values of B_t on B_n. $h = 4$ mm. $I \approx 30$ A. ■ - $B_t = 0.04$ T. ▲ – $B_t = 0.05$ T. ▼ – $B_t = 0.09$ T.

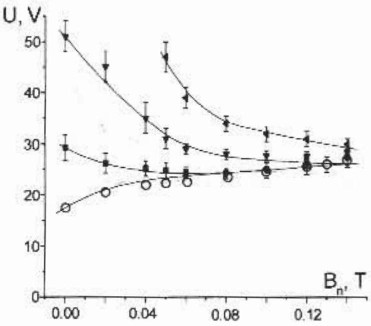

Fig. 4. Dependence of arc voltage on Cu cathode at different values of B_t on B_n. $h = 4$ mm. $I \approx 30$ A. ○ – $B_t = 0$ T. ■ – $B_t = 0.04$ T. ▼ – $B_t = 0.09$ T. ◀ – $B_t = 0.12$ T

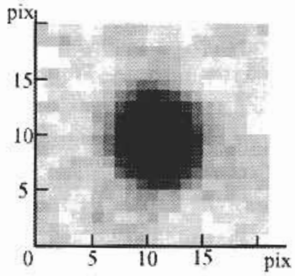

Fig. 5. Example of a CS image. 1 pix ≈ 0.067 mm.

Fig. 6 gives examples of the CS location determined from the photographic images. Fig. 6(a) shows mostly small differences in the CS frame-to-frame displacements but with several points exhibiting larger "jumps." These "jumps" are not, in our opinion, due to insufficient cleaning of the cathode surface, but may be attributable to other causes. First, under our processing method, when in the case of CS division where one brighter spot was selected, such an effect may be produced by arc branching (CS division). Second, we should take into account that the cathode image on the film has the shape of an ellipse with a semi axis ratio of about 1: (6–4) depending on the shooting angle, and, when the ellipse is transformed into a circumference, small accidental positioning errors increase substantially. Third, the jumps may be due to an instability of the arc.

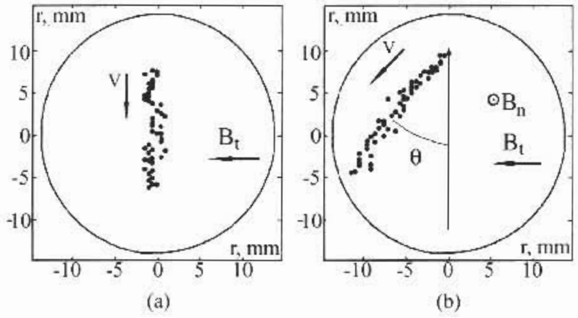

Fig. 6. Examples of processing of the photography results. $h = 4$ mm. $I \approx 30$ A. $B_t = 0.065$ T. (a) $B_n = 0$ T. (b) $B_n = 0.06$ T.

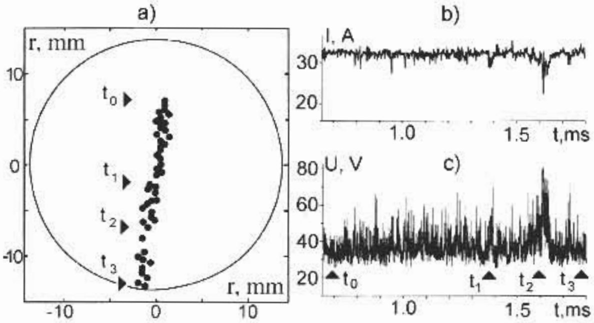

Fig. 7. Arc with a CuCr cathode. $h = 4$ mm, $I \approx 30$ A, $B_t = 0.06$ T. (a) Photography processing result. (b) Arc current. (c) Arc voltage. t_0, t_3: Start and stop of filming. t_1, t_2 mark the moments of arc voltage rises.

Fig. 7 shows a comparison between the CS motion pattern of unstable modes and the arc current and voltage in the corresponding time interval. The average velocity of the CS in the interval $t_0 - t_3$ is almost 50% larger than in the interval t_0–t_1. It should be noted also that the averaged path of the CS motion deviates by an angle $\approx 7^\circ$ from the direction of the retrograde motion, although no axial field was superimposed (B_n=0) and the coplanarity of the cathode planes and the coil axis of the transverse field was set with a higher accuracy (see Section II). The deviation of the averaged path in this case is also a consequence of arc instability. As seen from Fig. 7, the parts of the path, corresponding to time intervals $t_0 - t_1$, $t_1 - t_2$, and $t_2 - t_3$, do not practically deviate from the retrograde direction. The deviation of the path as a whole is a consequence of CS jumps. Therefore, when determining the speed and direction of the CS motion, we chose sufficiently long parts of the path, where the arc burning was steady.

In contrast to the arc voltage, the velocity of the retrograde motion depends on the degree of cathode surface erosion. Even when the surface is eroded throughout [Fig. 8(b)], further increase in the degree of the erosion [Fig. 8(c)] results in certain drop of the velocity [Fig. 8(a)]. Here, the character of the velocity dependence on the induction of the transverse magnetic field does not change. The dependence $V(B_t)$ remains linear $V = kB_t$.

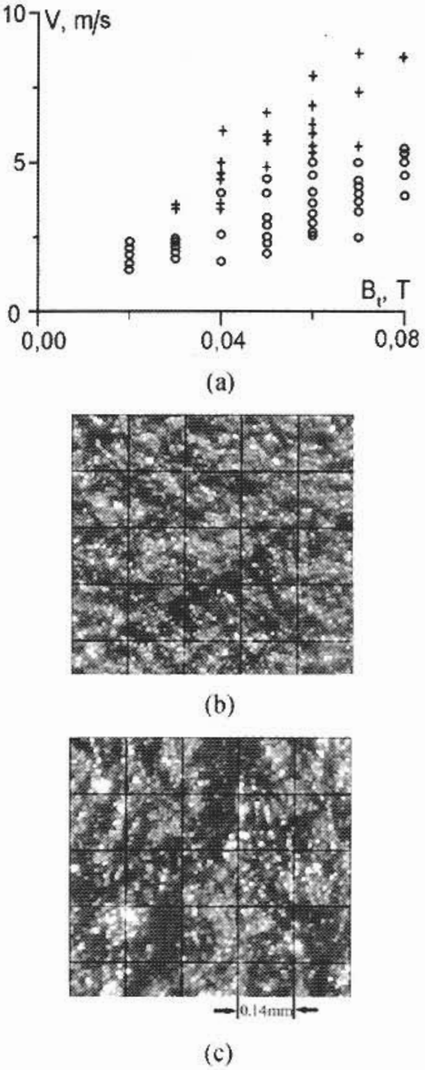

Fig. 8. Arc with a Cu cathode, $h = 4$ mm, $I \approx 30$ A. (a) Velocity of retrograde motion of CS in tangential magnetic field on throughout the eroded surfaces with a different degree of erosion. Crosses correspond to the surface shown in (b). Open circles correspond to the surface shown in (c). Cathode surfaces with different degree of erosion, the reference grid spacing 0.14 mm, (b) and (c).

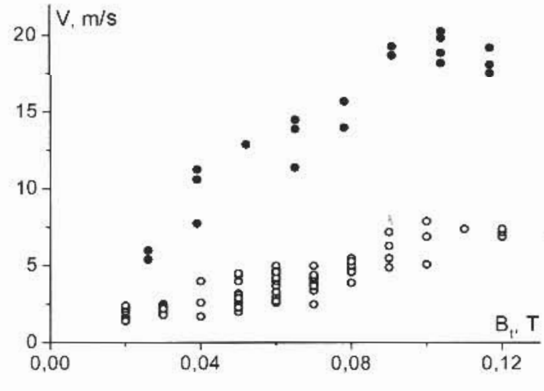

Fig. 9. Velocity of retrograde motion of CSs in a tangential magnetic field with an eroded surface. $h = 4$ mm, $I \approx 30$ A. Full circles: CuCr cathode. Open circles: Cu cathode.

Fig. 9 shows the comparison of the results of measurements of the velocities of retrograde CS motion on severely eroded cathodes of Cu and CuCr composition. The dependence of $V(B_t)$ on transverse magnetic field for the composite cathode in the studied range is also seen to be linear. The value of k can be estimated from these results as $k \approx 60$ m/(s · T) for the Cu cathode and as $k \approx 200$ m/(s · T) for the CuCr cathode.

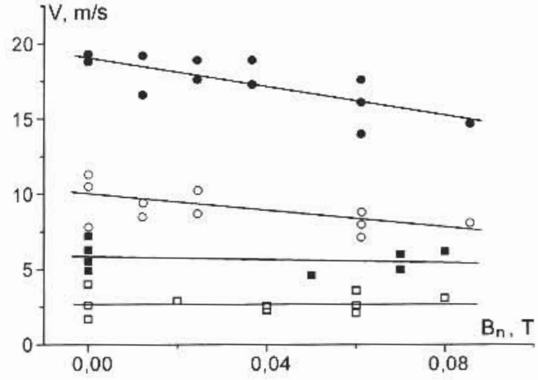

Fig. 10. Absolute magnitude of the CS motion velocity vector in magnetic fields with different B_t and B_n components. Circles: CuCr cathode. Squares: Cu cathode. Open symbols: $B_t = 0.04$ T. Full symbols: $B_t = 0.09$ T. $h = 4$ mm, $I \approx 30$ A.

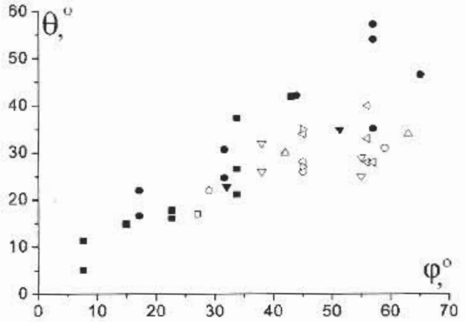

Fig. 11. Dependence of θ on φ. $h = 4$ mm, $I \approx 30$ A. Full symbols: CuCr cathodes. Open symbols: Cu cathode. Cu: □ – $B_t = 0.02$ T; ▷ – $B_t = 0.04$ T; ○ – $B_t = 0.05$ T; ◁ – $B_t = 0.06$ T; ▽ – $B_t = 0.07$ T △ – $B_t = 0.08$ T. CuCr: • – $B_t = 0.04$ T; ■ – $B_t = 0.09$ T; ▼ – $B_t = 0.13$ T.

Upon superposition of the axial magnetic field, the absolute value of the velocity vector of the CS motion somewhat decreases with the CuCr cathode, but remains practically constant with the Cu cathode (Fig. 10). The velocity vector rotates through an angle θ [Fig. 6(b)], whose value is independent of the magnetic field amplitude but is governed by the inclination angle φ of the induction vector with the cathode surface. The dependence of θ on φ for both studied materials is linear, yet the proportionality factors depend on the material (Fig. 11).

IV. DISCUSSION OF EXPERIMENTAL RESULTS

The data on the burning voltage of low-current arcs in magnetic fields are rather limited, as noted in the introduction. We can compare our results with the published data only for an arc with a Cu cathode in a transverse magnetic field. The results obtained in the present work are close to those of work [11]. We have not found in the literature any data on the burning voltage of arcs in a transverse field B_t coincident with an axial field B_n. The dependence of the arc voltage on B_n at a fixed value of B_t was found in the present work to be V-shaped. This is of interest from the viewpoint of the analysis of regularities found in the investigation of high-current arcs, stabilized by an external axial magnetic field.

In high-current arcs at fixed currents, the dependence of voltage on the induction of the axial field [Volt–Tesla characteristic (VTC)] is known to be V-shaped. With growing B_n, the VTC for different currents converges to a single curve. So, at high B_n the voltage of a high-current arc does not depend on current and is equal to that of low-current arc with a single CS [9].

It would be more accurate to speak of three typical parts of the VTC [12], [13]. In the first part, as the induction grows, the voltage across the arc drops fast. In the second part, it varies very little. And, finally, in the third part, the VTC exhibits a slow increase with voltage. The transition from the second part to the third for each VTC takes place when the voltage of the corresponding high-current arc becomes equal to that of the low-current arc.

From our data [14], at the second part of the VTC, practically all the CSs are located on the working surface of the cathode and cover it completely, i.e., the entire current of the arc near the cathode flows inside a circumference of a radius r equal to that of the electrode R. This allows estimating the value of the self-generated (transverse) magnetic field of the arc current at the electrode edge $B_t|_{r=R}$ at this part of the VTC. This field acts upon the CSs (and plasma jets flowing out of them) that are located at the periphery of the arc channel.

The analysis of the data published by various authors [9], [10], [14] and obtained with different materials in arcs of varying length ($2 \leq h \leq 10$) shows that, with growing B_n, the convergence of the VTC for different currents to a single curve takes place at $1 < B_n/B_t|_{r=R} < 2$. So, with the present work, we can conclude that the convergence of the VTC of high-current arcs and that of the $U(B_n)$ dependencies of low-current arcs occurs roughly at the same value of the ratio B_n/B_t.

Note that the results discussed above cast doubt on the calculations in [15], [16]. These papers did not take into account that the voltage across a cathode jet in the paraxial region of a high-current arc ($B_t = 0$) can differ greatly from that across a jet at the periphery in those modes of arc burning where $B_n/B_t|_{\mathrm{r=R}} < 1$. Yet such modes were considered in them. Results given on Figs. 3 and 4 in the present work actually call the main concept of the work [16] in question. The work deals with the transition of a high-current arc from a "diffuse column mode" to a "diffuse mode." The transition is claimed to take place when the voltage across the arc drops to the level corresponding to that across the cathode jet. If the arc voltage is higher, individual jets cannot exist outside the main channel. We cannot concur with this, as such jets would be subjected to the action of the transverse field generated by the main channel of the arc. The voltage across them would vary greatly depending on specific conditions of the arc current, current channel diameter, and axial field induction.

Let us discuss the measurements of the CS motion velocity. The dependence of the velocity $V(B_t)$ of the retrograde CS motion on a severely eroded surface on magnetic field induction at $I = 30$ A, $h = 4$ mm, $B \leq 0.12$ T proved to be linear for both studied materials (Cu, CuCr). In the case of the Cu cathode, the result agrees with known data, with the exception of the work [6]. In the latter, the dependence $V(B_t)$ for a "virgin smooth cathode" of Cu at $h = 3$ mm was exponential. Yet, for an "eroded" Cu cathode in a quite short arc at $h = 1$ mm, the dependence $V(B_t)$ proved to be linear. To supply the arc, the author of [6] used a battery providing 144 V. The following explanation can be proposed.

The stability of a low-current arc decreases as the induction of the transverse magnetic field grows. Our work reveals (Fig. 7) that it causes an apparent increase in the CS motion velocity. The linear dependence of $V(B_t)$ on an eroded cathode was obtained in [6] in an arc of length $h = 1$ mm, which burns more steadily at the same value of B_t. An exponential dependence of $V(B_t)$ with a "virgin smooth cathode" was obtained in a longer ($h = 3$ mm) and, hence, less steadily-burning arc. For the same reason, an "exponential" dependency of $V(B_t)$ was given in [6] for a CuCr cathode, but it was obtained with an arc of length $h = 3$ mm. Note that, e.g., in [11], the arc was supplied by a source voltage of 450 V.

The values that we obtained for the velocity constant k of retrograde spot motion on severely eroded copper surfaces are close to that obtained in [6]. Nevertheless, an exact comparison is impossible since the data in [6] are given for a greater current (50 A) and shorter arc length ($h = 1$ mm). The degree of the surface erosion is also difficult to compare. The work [11] reported for an arc with current 30 A and length $h = 1.5$ mm the value $k \approx 20$ $\mathrm{m/(s \cdot T)}$. One can recalculate the value to $h = 4$ mm with the help of the dependence of the velocity on arc length, given in that work. The recalculated value proves to be roughly one-half of the value we obtained. The following explanation of the discrepancy is possible.

It was noted in [11] that the velocity of the CS motion depends on the pulse number; strongly at first and then, more weakly. After ~ 100 pulses, the velocity practically stops changing. Note that here, in each pulse, a CS moved strictly along the very same part of the cathode surface, whose erosion became finally quite significant. That is, actually, the CS moved in a "groove" it had "dug." Our work used a high-current cleaning pulse, and because of that the cathode surface became uniformly, but also severely eroded. Such conditions of the surface seem to be more relevant to those realized in high-current vacuum switching gear. Besides, in work [11], the anode was of pure graphite. The reason underlying this choice was unexplained. Meanwhile, graphite conductivity is almost 500 times (!) lower than that of copper and comparable to that of the arc plasma. The CS moves in the retrograde direction, whereas the arc channel deviates in the opposite direction, and the anode attachment "lags" behind the spot. Depending on the design of the current lead to the graphite anode, a situation may arise where the arc would, by seeking the minimum voltage, brake the motion of the anode attachment and, along with it, that of the cathode. It should be noted that the work under discussion reports a surprisingly small scatter in both the results of measurements of the CS velocity and those of the arc burning voltage. In our work, the scatter in velocity values was as high as a factor of two. In work [6], the scatter proved to be still more, whereas in work [11, Fig. 6], a mere 10–15% (!).

We have found in the literature no data on the influence of the axial magnetic field upon the magnitude of the velocity of the CS motion in a low-current arc in a transverse magnetic field. In a number of works, e.g., [14], [17], it was noted that the expansion rate of the cathode attachment upon the initiation of a high-current arc, stabilized by an axial magnetic field, decreases significantly with growth of the induction of the axial field. In [17], the expansion rate of the cathode attachment was identified with the velocity of retrograde CS motion in the self-generated field of the arc current, including under superposition of an axial field upon the arc. On these grounds, it was concluded that the velocity of the retrograde CS motion strongly depends on the axial field induction. From the data here presented, the absolute magnitude of the CS motion velocity on a Cu cathode does not practically depend on B_n, while with a CuCr cathode it changes slightly. But there is a strong effect related to the rotation of the velocity vector through some angle θ, which depends on the ratio of the resultant field components (Fig. 11). Thus, the expansion rate of the cathode attachment upon the initiation of a high-current arc stabilized by a magnetic field cannot (in contrast to the freely burning arc [18]) be identified with the velocity of retrograde motion. The considerable decrease of the expansion rate of the cathode attachment of a high-current arc is the result, first of all, of the lengthening of the paths followed by the CSs and their transformation from straight lines (in freely burning arcs) into helices.

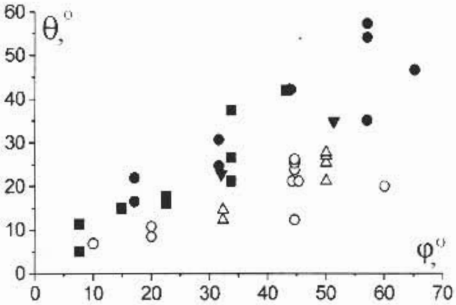

Fig. 12. Dependence of θ on φ, $h = 4$ mm, $I \approx 30$ A. Full symbols: CuCr cathodes. Open symbols: Mo(○) and C(△) cathode [8].

As already mentioned in the introduction, we are aware of only one work [8] dealing with measurements of the dependence of angle θ of the CS motion path deviation on the inclination angle φ of the magnetic field on clean surfaces. The comparison of the results obtained in the present work on CuCr cathodes with those of the work quoted is given in Fig. 12. Significant divergence in the results is observable. One can suppose that the disagreement between our data and those in [8] may be attributable just to the difference in cathode materials. Definite difference obtained in our work with Cu and CuCr cathodes (Fig. 11) render such a supposition quite plausible. Of undoubted interest is further study, including the use of various cathode materials.

V. CONCLUSION

The experimental study carried out shows the following.

1) The dependences of the voltage U across a low-current arc on the induction of axial magnetic field B_n for various values of the tangential field induction B_t are typically V-shaped.
2) This dependence converges to a single curve corresponding to $B_t = 0$ at $B_n/B_t \geq 1.5$.
3) The velocity of the CS retrograde motion on both Cu and CuCr cathodes linearly depends on B_t. The proportionality factor k depends on the degree of surface erosion. It depends also on the arc stability.
4) The dependence of the absolute value of the CS velocity vector on B_n is slight. The strong effect is the rotation of the

velocity vector through the angle, dependent on the ratio B_n/B_t. The angle also depends on the cathode material. This completed analysis proves that the convergence of the VTC of high-current arcs and that of the $U(B_n)$ dependence of low-current arcs occurs roughly at the same value of the ratio B_n/B_t.

ACKNOWLEDGMENT

The authors express their gratitude to S. I. Malakhovsky for helpful discussion and continuous support of this work and to S. P. Korop, R. A. Zhuk, and Y. O. Avvakumov from IG Tavrida Electric, who have developed and manufactured the power source and control console used in the present work.

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