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ABSTRACT
This paper aims to investigate the dynamic characteristics of vacuum metal vapor arcs under rotating and traditional direct contact separation modes. Non-symmetrical pure copper electrodes with an anode radius of 7.5 mm and a cathode radius of 22.5 mm are employed in the experiments. The permanent magnet actuator provides an average opening speed of 1.0 m/s for cathode direct separation and 1–3 deg/ms for rotation. Results show that electrode rotation significantly influences the distribution and motion speed of the arc root on the cathode surface.

I. INTRODUCTION
The separation of contacts in a vacuum switch induces arc formation, accompanied by pronounced material transfer, arc root agglomeration, and stagnation, resulting in electrode surface ablation and the formation of molten craters.1,2 The vacuum arc, essentially a metal vapor arc, relies significantly on cathode spots as the primary source of metal vapor in the inter-electrodes vacuum space. These cathode spots dictate the fundamental attributes of the vacuum arc and directly impact the interruption capability of vacuum switches. The arc root is formed by the aggregation of many simultaneously existing microscale cathode spots into one or more approximately circular foot points. Therefore, an investigation into the motion characteristics of the vacuum metal vapor arc root proves instrumental in comprehending the intricacies of the vacuum arc, bearing substantial relevance for the optimization design of vacuum switches.

At present, research on the plasma of vacuum arcs uses mainly two methods: modeling and simulation16,17 and experimental investigations. Wang et al.21 proposed a model with six cathode spot plasma jets distributed at a specific distance from the cathode center. Simulation results reveal that the angle, inclined flow, and varying heights of the mixing zone in vacuum arc jets can influence the mixing and interaction of multi-cathode spot vacuum arc jets. Li et al.22 established a model for dual cathode spot ablation, simulating the evolution process of ablation craters when two spots coexist, and analyzing the formation mechanism of cathode spot clusters. Jing et al.,12 employing a model of cathode spots between contacts under a transverse magnetic field, simulated the motion and distribution of cathode spots and studied the characteristics of the initial diffusion stage of cathode spots between TMF (Transverse Magnetic Field) contacts.

In the absence of external magnetic field interference, cathode spots exhibit random motion on the cathode surface. Song et al.13 investigated the impact of axial magnetic fields on the initial expansion velocity of cathode spots during the initiation stage of vacuum arc triggering. The study indicates that the expansion velocity of cathode spots increases with the rising rate of current but the curvature and extension of cathode spot trajectories alone are insufficient to explain the observed increase when the magnetic field diminishes. Under transverse magnetic field conditions, Pang et al.14,15 investigated the local high-temperature hindrance effect on arcs caused by vacuum arc stagnation. The findings suggest that arc duration not only influences arc speed but also significantly affects the morphology of the arc during the diffusion stage. Moreover, peak current and electrode diameter impact the cathode spot movement characteristics during the diffusion stage. Liu et al.16 experimentally investigated the behavior of cathode spots in high di/dt vacuum arcs,
revealing the influence of different current amplitudes, frequencies, and \( \frac{dI}{dt} \) conditions on the movement characteristics of cathode spots. Ma et al.\(^{17} \) explored the effects of a rotating transverse magnetic field on the unstable state of cathode spot clusters in direct current vacuum arcs and summarized the relationship between arc transient behavior and arc voltage characteristics.

Current research mainly focuses on the impact of transverse and axial magnetic fields on the motion characteristics of vacuum arcs. A key factor influencing the transition of arc modes from a constriction-based arc to a diffusion state is the rapid disruption of the arc root stagnation state between electrodes.\(^{19} \) This paper proposes a novel breaking method involving the rotation of contacts. Specifically, during the operation of a vacuum switch, a clockwise rotational motion is introduced in addition to the linear motion of the cathode. We have developed a vacuum arc initiation experimental system with rotating contacts and captured the entire process of the vacuum metal vapor arc using a high-speed camera. The influence of contact rotation on arc characteristics is experimentally studied, and a method for restoring the real three-dimensional world coordinates of arc roots is designed. This research provides a research foundation for further exploration of the application of rotating breaking mechanisms in vacuum switchgear.

II. EXPERIMENTAL SETUP

Figure 1 shows the experimental platform for arc initiation with rotating contacts, comprising five main components: the vacuum system, a detachable vacuum arc extinguishing chamber, a mechanical drive system, a high-speed imaging system, and a signal acquisition system. Throughout the experiment, the vacuum system operates continuously to maintain the vacuum pressure inside the detachable arc extinguishing chamber above \( 10^{-4} \) Pa. The vacuum arc extinguishing chamber is equipped with a quartz glass observation window to directly record and observe the motion of the contacts and the evolution of the arc. The contacts are insulated from the extinguishing chamber, and on the cathode side, they are connected to a permanent magnet actuation mechanism, achieving circuit switching through electromagnetic attraction and repulsion. During the experiment, the direct current power supply provides the main circuit current, and through a load resistor, the electrical control system executes synchronous separation commands. The contact system separates to generate the arc using either a single linear motion or a linear-rotational synchronous motion. The high-speed imaging system is configured with a maximum frame rate of 7500 fps and a frame interval of 133.33 μs. The electrical parameters of the arc, such as current and voltage, are measured using voltage and current probes. The high-speed camera and associated optical systems are under the control of the main controller to ensure synchronized image capture of the vacuum arc. To better observe the entire process of arc formation and development, the experiment employs an asymmetrical flat contact structure, featuring a cathode contact radius of 22.5 mm, an anode contact radius of 7.5 mm, and copper as the contact material. Prior to the experiment, the recording angle is adjusted to ensure a clear observation of the entire gap and cathode surface, with experimental conditions set at a DC current of 60 A, a gap voltage of 50 V, and an average separation speed of the cathode linear motion mechanism set at 1.0 m/s, as shown in Fig. 2. The average rotational speeds of the contacts are respectively set at 1, 2, and 3 deg/ms.

To observe the motion characteristics of the arc, the experiment primarily emphasizes observing the movement of the arc root in tandem with the motion of the cathode-side contact. Consequently, the camera predominantly captures the cathode surface. Owing to experimental conditions and the camera’s shooting angle, the circular cathode contact surface appears elliptical in the camera coordinates. The images captured by the camera represent two-dimensional pixel maps that lack depth information. They provide a relative perspective on the arc root movement but do not faithfully convey the real-time three-dimensional spatial vector of the arc root.

For a more thorough exploration of the arc root’s motion characteristics, a crucial step involves transforming the two-dimensional pixel maps of the arc root obtained from the camera into three-dimensional spatial coordinates.

III. ARC IMAGE PROCESSING

Figure 3 shows that the point \( C(X_c, Y_c, Z_c) \) represents the coordinates in the camera coordinate system corresponding to a three-dimensional world coordinate point \( P(X_w, Y_w, Z_w) \). The image coordinate system \( p(x, y) \) is used with a pixel-to-millimeter scale factor of 8.489 pixels/mm.

To perform the transformation from two-dimensional to three-dimensional coordinates, three primary conversion steps are
involved, encompassing four key coordinate systems: the camera coordinate system, the world coordinate system, the image coordinate system, and the pixel coordinate system. The interrelations among these coordinate systems are depicted in Fig. 4:

The camera coordinate system is a three-dimensional spatial coordinate system that establishes a connection between the world coordinate system and the image coordinate system. Assuming the camera coordinate system has its origin at the center of the camera, its XY axis aligns with the xy axis of the image coordinate system. The Z axis is perpendicular to the imaging plane and points toward the image plane. The intersection of the Z axis and the image plane coincides with the origin of the image xy coordinate system. In this configuration, the Z coordinates of all pixels on the image plane in the camera coordinate system equal the focal length \( f \). Thus, for a pixel point \( p \) with coordinates \((x, y)\) in the image coordinate system, its coordinates in the camera coordinate system are represented as \((x, y, f)\).

According to the characteristics of central projection, assuming the world coordinate point \( P \) is projected onto the image coordinate as pixel point \( p \), the corresponding spatial coordinates of pixel point \( p \) in the camera coordinate system are denoted as \( C(X, Y, Z) \). If two points lie on the same straight line emanating from the origin of the coordinate system, their coordinates will exhibit a proportional relationship, that is,

\[
\frac{x}{X} = \frac{y}{Y} = \frac{f}{Z}. \tag{1}
\]

The same is represented in matrix form as follows:

\[
\begin{bmatrix}
    x \\
    y \\
    1
\end{bmatrix}
= \begin{bmatrix}
    \frac{1}{d_x} & 0 & u_0 \\
    0 & \frac{1}{d_y} & v_0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    X \\
    Y \\
    Z
\end{bmatrix}. \tag{2}
\]

Through the conversion of the \( xy \) coordinate system into the \( uv \) coordinate system and incorporating the aforementioned equation, the transformation of the camera coordinate system \((X, Y, Z)\) into the \( uv \) coordinate system can be accomplished, thus,

\[
\begin{bmatrix}
    x \\
    y \\
    1
\end{bmatrix}
= \begin{bmatrix}
    \frac{f}{d_x} & 0 & u_0 \\
    0 & \frac{f}{d_y} & v_0 \\
    0 & 0 & \frac{1}{Z}
\end{bmatrix}
\begin{bmatrix}
    X \\
    Y \\
    Z
\end{bmatrix}.
\tag{3}
\]

Commonly, \( Z_c \) is referred to as the scale factor \( \lambda \) and the intermediate \( 3 \times 3 \) matrix is known as the intrinsic matrix \( K \). Clearly, the intrinsic matrix \( K \) characterizes the transformation from the camera coordinate system to the \( uv \) coordinate system. The expression is formulated as follows:

\[
\lambda p = KPc. \tag{4}
\]

The intrinsic matrix \( K \) stands as a pivotal parameter for the camera. \( \frac{d_x}{f} \) and \( \frac{d_y}{f} \) effectively represent the conversion of the physical focal length \( f \) into pixel units, where \( \frac{d_x}{f} \) and \( \frac{d_y}{f} \) denote the pixel-unit values of the focal length in the two pixel directions. The ultimate matrix expression for the intrinsic parameters is as follows:

\[
K = \begin{bmatrix}
    \frac{d_x}{f} & 0 & u_0 \\
    0 & \frac{d_y}{f} & v_0 \\
    0 & 0 & 1
\end{bmatrix}. \tag{5}
\]

Using a calibration board, multiple sets of photographs were captured from diverse positions and angles to determine the intrinsic matrix. The procedural details are shown in Fig. 5.

The world coordinate system, being a 3D and absolute coordinate system, unifies all particles in space under a common coordinate framework. In the camera calibration process of this experiment, the center point of the anode contact within the field of view is established as the origin of the world coordinate system. The calibration involves mapping the top-left corner point of the calibration board to this center point:

\[
\lambda \begin{bmatrix}
    u \\
    v \\
    1
\end{bmatrix}
= \begin{bmatrix}
    \frac{d_x}{f} & s & u_0 \\
    0 & \frac{d_y}{f} & v_0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    X_c \\
    Y_c \\
    Z_c
\end{bmatrix}. \tag{6}
\]
The transformation between the world coordinate system and the camera coordinate system can be achieved through rotation and translation, as shown in Fig. 6.

A spatial point \( P(X_w, Y_w, Z_w) \) can be transformed into camera coordinate system coordinates \((X_c, Y_c, Z_c)\) by employing a 3 x 3 unitary orthogonal rotation matrix \( R \) and a 3 x 1 translation vector \( t \):

\[
\begin{bmatrix}
X_c \\
Y_c \\
Z_c
\end{bmatrix} = R_{3\times3} \begin{bmatrix}
X_w \\
Y_w \\
Z_w
\end{bmatrix} + t_{3\times1} = \begin{bmatrix}
X_w \\
Y_w \\
Z_w
\end{bmatrix}.
\]  

(7)

The rotation matrix \( R \) and translation vector \( t \) constitute the extrinsic matrix of the camera, depicting the transformation from the world coordinate system to the camera coordinate system. To characterize the transformation relationship between the camera and the world coordinate system, the rotation matrix \( R \) for converting the camera coordinate system to the world coordinate system and the position \( C \) of the camera’s focal point in the world coordinate system are employed as extrinsic parameters, as shown in Fig. 7.

Then the transformation from the world coordinate system to the camera coordinate system is given by

\[
\begin{bmatrix}
X_c \\
Y_c \\
Z_c
\end{bmatrix} = \begin{bmatrix}
R_{3\times3} & t_{3\times1}
\end{bmatrix} \begin{bmatrix}
X_w \\
Y_w \\
Z_w
\end{bmatrix}.
\]
\[
P_c = \begin{bmatrix} R & t \\ 1 \end{bmatrix} \begin{bmatrix} P_w \\ 1 \end{bmatrix}.
\]

In 3D reconstruction from images, the image coordinate system "uv" is typically the input and the world coordinate system is the output. Based on Eqs. (6)–(8), we have

\[
\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = K \begin{bmatrix} R & t \\ 1 \end{bmatrix} \begin{bmatrix} P_w \\ 1 \end{bmatrix} = M \begin{bmatrix} P_w \\ 1 \end{bmatrix},
\]

\[
M = K \begin{bmatrix} R & t \\ 1 \end{bmatrix}.
\]

Separating from (11), we obtain

\[
z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = K \begin{bmatrix} R_{3 \times 3} & t_{3 \times 1} \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}.
\]

Considering \(P^{-1}P = E\), the inverse transformation from the 2D coordinate system to the 3D coordinate system can be derived:

\[
z_c K^{-1} = R_{3 \times 3} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} = R \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} + t.
\]

Therefore, we have

\[
R^{-1} \cdot \left( K^{-1} \cdot z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} - t \right) = \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix},
\]

\[
z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = R^{-1} \cdot \left( K^{-1} \cdot z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} + R^{-1} \cdot t \right).
\]

Assuming \(M_1 = R^{-1} \cdot K^{-1} \cdot \begin{bmatrix} u \\ v \\ 1 \end{bmatrix}\) and \(M_2 = R^{-1} \cdot t\), it is deduced from the context of

\[
z_c \cdot M_1[2] = Z_w + M_2[2].
\]

Therefore,

\[
z_c = \left( z_c + M_2[2] \right) M_1[2].
\]

According to Eqs. (12)–(17), the three-dimensional world coordinates of the arc root position can be determined.

IV. RESULTS ANALYSIS

According to the analysis described above, Python code was developed to reconstruct 3D world coordinates from the 2D pixel coordinates of the captured images. The specific procedure is outlined below:

1. Multiple sets of images were captured at different positions and angles using a calibration board (with each grid having a side length of 3 mm) to obtain camera intrinsic parameters.
2. The world coordinate origin [center of the upper contact post \(O(0, 0, 0)\)] was calibrated with the left upper corner point \([O_1(0, 12.3, 0)\)], ensuring that the camera lens was parallel to the calibration board plane. The camera’s extrinsic parameters were determined, and the camera’s shooting angle and focal length were kept constant throughout the experiment.
3. 100 experiments each of direct pull and rotating disconnection at different speeds were conducted. Images were captured and collected for each experiment, and the average disconnection time was calculated for each set of 100 experiments. The set with the closest average arc duration was selected.
4. Pre-processing was applied to the captured images, including image enhancement, filtering, edge extraction, and other operations, as shown in Fig. 8.
5. Implement region-of-interest (ROI) processing on the elliptical contour of the cathode surface to extract information regarding the position, size, and distortion of the elliptical surface.
6. Apply perspective transformation to the processed elliptical surface and utilize image binarization along with connected component analysis to determine the locations of spots and contact points on the cathode surface.
7. Conduct perspective analysis and coordinate transformation, considering the pixel-to-real-world scale relationship, to obtain actual three-dimensional coordinates, as illustrated in Fig. 9.

After binarizing the images, the contour of the arc root can be determined, and the connected component analysis method is employed to determine the coordinates of the contact point between the arc root and the cathode electrode surface at that moment.
Setting the initially clear-captured position of the arc plasma as the reference (position value equals zero), the relative displacement of the arc plasma position at different times is calculated. This enables the plotting of a curve that displays the variation of the arc plasma position over time. Randomly selecting a dataset from experiments involving direct separation of contacts and separation with three different contact rotation speeds, the actual position of the arc root at each moment is restored to the contact point based on the aforementioned method, as shown in Fig. 10. (a) represents the entire process from the first frame of arc image captured by the camera to the last frame before the arc extinguishes, depicting the variation of arc root distribution on the contact surface under the action of direct contact movement of the contactor, and the resulting arc root movement velocity; (b), (c), and (d) represent the variation of arc root distribution on the contact surface and the resulting arc root movement velocity under different contactor rotation speeds. In the arc root distribution image, the red dots represent the coordinates of the arc root and the connecting lines represent the distance the arc root moves from one coordinate point to the next. The envelope line in the diagram represents the movement path of the diffused arc after leaving the contact area of the dynamic and static contacts on the cathode contact surface, extending continuously until the contact extinguishes.

Therefore, the instantaneous displacement velocity of the arc root can be calculated using Eq. (18):
FIG. 10. Distribution of arc root positions and velocities.
Here, $\Delta P_w$ denotes the three-dimensional displacement of the arc root between two consecutive images and $\Delta t$ represents the time interval between two successive images.

To further investigate the dynamics of arc root movement and ensure minimal error influence on the research outcomes, 100 repetitive single discharge tests were performed under identical discharge conditions for both direct contact separation and contact separation with different rotational speeds. Throughout these tests, imaging conditions were rigorously maintained at uniform settings.

Figure 10 shows that it is evident that under direct contact separation conditions, the distribution area of the arc root is relatively dense. In the case of contact separation with rotation, the area on the electrode where the arc root is distributed increases with the increment of the cathode rotation speed. The solid lines connecting the arc roots represent their motion trajectories during the diffusion phase. For direct separation mode, the motion characteristics of arc roots are similar to those without an external magnetic field; both exhibit a random-walk-like pattern. However, under rotation, the movement of the arc root generally aligns with the clockwise direction of the electrode rotation. It is worth noting that there is still a degree of randomness, and the term “consistent direction” refers to a statistical sense—where the majority of arc roots align with the cathode rotation direction, with occasional instances of opposite alignment. The figure also illustrates that the rotation of the electrode has varying effects on the arc root’s velocity. Compared to direct separation, the arc root’s velocity is higher, and with an increase in rotation speed, the arc root’s velocity also increases.
As described in the text, 100 experiments were conducted for each breaking method condition. To minimize experimental errors, different breaking methods were grouped, and within each group, five experiments with similar breaking times were randomly selected. The arc root positions for each experiment were then reconstructed, and the arc root movement speed was calculated to obtain the average speed value. The five average speed values obtained for each group are listed in Fig. 11, representing the trend of different breaking methods on the average arc root movement speed. It can be observed that under the cathode rotation method, the average arc root movement speed is significantly higher than that under the direct movement method, and as the rotation speed increases, the arc root speed also increases accordingly, showing a consistent overall distribution and trend of variation.

As shown in Fig. 12, the gradual separation of contacts results in the elongation of the arc, accompanied by a corresponding increase in arc resistance. When the arc extends to a specific length, providing a sufficient channel for energy release, there is a sharp decline in arc current. The rotational effect of the cathode further elongates and distorts the arc, accelerating the reduction in energy. Analysis of the collected data and experimental observations suggests that the vacuum arc undergoes a transition from a constricted arc to a diffused arc around the point of an abrupt decrease in arc current. Initial observations of constricted arcs reveal a bridge-pillar shape with a distinct conducting channel in the middle. Observing the entire process of arc breaking, when the contact directly pulls, the whole arcing time is 9.15 ms, and the arc current drop point is at 6.85 ms. Under the rotating contact method, when the rotation speed is \( \omega = 1 \) deg/ms, the whole arcing time is 8.3 ms and the arc current drop point is at 5.85 ms; when \( \omega = 2 \) deg/ms, the whole arcing time is 7.7 ms and the arc current drop point is at 5.55 ms; when \( \omega = 3 \) deg/ms, the whole arcing time is 6.48 ms and the arc current drops abruptly at 3.14 ms during the first stage. It can be observed that the rotational arc exhibits an earlier decrease in current and a shorter arcing time compared to the straight pulling arc. When the current sharply decreases, the emission of metal vapor from the cathode to the arc gap diminishes, resulting in reduced arc energy and the rapid transition of the arc from a confined state to a diffused state.

In the initial stages of contact separations, the arc root tends to linger on the cathode surface. As arc energy is introduced into the cathode surface, this region undergoes material melting and vaporization. With an increase in arc energy, splashing phenomena may occur, leading to the formation of irreversible ablation traces on the cathode surface due to the influence of arc pressure and energy. Consequently, the cathode surface loses its smoothness, thereby impacting the interruption process of the switchgear.

In Fig. 13, the cathode ablation caused by a 60 A current under both direct and rotational motion conditions in a vacuum arc is depicted. The figure illustrates the distinctive trajectories of eroded pits on the cathode surface. The rotational effect of the cathode reduces the dwell time of arc energy at specific points, resulting in increased relative movement between the cathode surface and the arc. It is observed that during rotation, the cathode’s surface ablation area is larger compared to direct motion, with a shallower ablation depth. This is attributed to the rotational motion altering the center position of the arc action, leading to an increased ablation area. However, the arc root dwells for a shorter time at each position, reducing the time required for temperature transfer and resulting in a shallower ablation depth. Measurements indicate that under direct motion, the ablation area is 16.853 mm². For rotational motion at \( \omega = 1 \) deg/ms, the areas of two eroded pits on the cathode surface are 19.388 and 3.160 mm², resulting in a total damaged area of 22.548 mm². At \( \omega = 2 \) deg/ms, the areas of the two eroded pits are 8.669 and 29.791 mm², with a total damaged area of 38.46 mm². At \( \omega = 3 \) deg/ms, the area of the eroded pit from rotational motion is 42.826 mm².

The contact mass was measured using the Bel Engineering HPBG semi-microbalance, with a sensitivity of 0.01 mg. Based on the ablation mass obtained from a large number of symmetric cathode breaking experiments, the summary is presented in Table 1. The term “ablation” refers to the process of material removal from a surface due to the action of an arc. The ablation mass obtained here is a measure of the material lost from the cathode surface due to the arc action. The table data represents the average ablation mass for different contact separation modes.

### TABLE I. Cathode ablation mass under different contact separation modes.

<table>
<thead>
<tr>
<th>Group</th>
<th>( \omega = 0 ) deg/ms (mg)</th>
<th>( \omega = 1 ) deg/ms (mg)</th>
<th>( \omega = 2 ) deg/ms (mg)</th>
<th>( \omega = 3 ) deg/ms (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.8</td>
<td>1.2</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
<td>1.1</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>1.1</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Mean ablation mass</td>
<td>1.56</td>
<td>1.13</td>
<td>0.933</td>
<td>0.7</td>
</tr>
</tbody>
</table>
is superior to that under straight separation. After conducting the same number of breaking experiments (100 times), the ablation mass under rotational breaking was found to be lower than that of straight-line breaking. The analysis of cathode ablation indicates that with an increase in cathode rotation speed, the ablation volume decreases, resulting in a reduction in cathode ablation mass. Under identical experimental conditions, rotational separation proves to be more effective in minimizing material loss from the contacts compared to straight separation.

V. CONCLUSIONS

This paper proposes a novel breaking method using vacuum rotational electrodes and establishes a vacuum arc drawing experiment platform. The study investigates the influence of electrode rotation on the movement characteristics of arc roots on the cathode, designs a method to reconstruct the three-dimensional spatial coordinates of arc roots on the cathode, and explores the effect of electrodes on cathode ablation. The main findings are as follows:

1. The rotational motion of the contact significantly enhances the distribution range of the arc root on the cathode surface, leading to an expanded radial movement range of the diffuse arc root toward the edge of the cathode and an increase in the arc root’s movement velocity. Consequently, this results in a shorter vacuum arc breaking time.

2. The rotational motion of the contact swiftly disrupts the stagnation of the arc root on the electrode surface, expediting the transition of the vacuum arc from a limiting arc to a diffuse arc. The time point of transition for the initial limiting arc motion is advanced.

3. The rotational motion of the contact significantly improves the electrode ablation conditions. Although the ablation area increases, the ablation depth significantly decreases, resulting in a noteworthy reduction in ablation mass.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Zhengbo Li: Investigation (equal); Methodology (equal); Supervision (equal); Validation (equal); Writing – review & editing (equal). Si Fu: Conceptualization (lead); Data curation (lead); Funding acquisition (equal); Investigation (lead); Methodology (lead); Project administration (lead); Supervision (equal). Yundong Cao: Conceptualization (equal); Formal analysis (equal); Project administration (equal); Resources (equal); Software (equal); Validation (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES


