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STUDY ON ARC EVOLUTION BEHAVIOUR OF BREAKING SHORT CIRCUIT CURRENT FOR A FAST VACUUM CIRCUIT BREAKER

OSTUDIJA PONAŠANJA RAZVOJA LUKA PRI PREKIDANJU STRUJE KRATKOG SPOJA BRZIM VAKUUMSKIM PREKIDAČEMF

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Abstract: A fast vacuum circuit breaker (FVCB), driven by an electromagnetic repulsion mechanism, has an extremely short opening time, and in coordination with the controlled switching technology contributes to breaking a short circuit current with the minimum arcing time. The objective of the paper is to determine the arc evolution behaviour of fast vacuum circuit breakers with a minimum arcing time. A 40.5 kV vacuum interrupter (VI) was used, which was equipped with a pair of CuCr50 (Cr 50 wt%) axial magnetic field (AMF) contacts. The diameters of the contact were Φ50mm, Φ58 mm and Φ65 mm respectively. The arc evolution behaviour in the drawn arc experiment was photographed by a high-speed camera through a glass envelope of the VI. The experiment results showed that an initial intense arc tended to evolve into a diffuse arc when the arcing time is larger than a critical arc diffusion time under a certain opening velocity. The critical arc diffusion time for the vacuum arc is defined as arc evolving from the instant of contact separation to an appearance of separated cathode spots. For a Φ50 mm cup-type AMF contact, the critical arc diffusion time decreases from 0.7 ms to 0.46 ms, with the increase of the opening velocity from 2.52 m/s to 4.65 m/s. What's more, for a Φ58 mm cup-type AMF contact, the critical arc diffusion time decreases from 1.0 ms to 0.58 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s. For a Φ65 mm cup-type AMF contact, the critical arc diffusion time decreases from 1.30 ms to 0.64 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s. The critical arc diffusion time increases with the increase of the diameter of the contact under the same opening velocity.

Keywords: Arc evolution behaviour, critical arc diffusion time, electromagnetic repulsion mechanism, fast vacuum circuit breaker, short-circuit current breaking, minimum arcing time

Sažetak: Brzi vakuumski prekidač (FVCB), koji je pogonjen mehanizmom elektromagnetne repulzije i ima izuzetno kratko vrijeme isklopa, u suradnji sa upravljivom sklopnom tehnologijom doprinosi prekidanju struje kratkog spoja sa minimalnim vremenom trajanja luka. Cilj ovog rada je da ispita ponašanje razvoja luka u brzim vakuumskim prekidačima sa minimalnim vremenom trajanja luka. Korišten je 40.5 kV vakuumski sklopni element (VI), koji je opremljen sa parom CuCr50 (Cr 50 wt%) kontakata u aranžmanu aksijalnog magnetnog polja (AMF). Promjeri kontakata su Φ50mm, Φ58 mm i Φ65 mm, respektivno. Ponašanje razvoja luka u izvedenom eksperimentu je snimano brzom kamerom kroz stakleni prorez na VI. Rezultati eksperimenta pokazuju da inicijalni intenzivni luk teži da preraste u difuzni luk kada je trajanje luka duže nego kritično vrijeme difuzije luka pri odgovarajućoj brzini isklopa. Kritično vrijeme difuzije luka za luk u vakuumu je definirano kao vrijeme razvoja luka od trenutka razdvajanja kontakata do pojave razdvojenih katodnih tačaka. Za Φ50 mm AMF kontakt kupolastog tipa, kritično vrijeme difuzije luka se smanjuje od 0.7 ms do 0.46ms sa povećanjem brzine isklopa od 2.52 m/s do 4.65 m/s. Štaviše, za Φ58 mm kupolasti AMF kontakt kritično vrijeme difuzije luka se smanjuje od 1.0 ms do 0.58 ms sa povećavanjem brzine isklopa od 2.52 m/s do 4.65 m/s. Za Φ65 mm AMF kontakt, kritično vrijeme difuzije opada sa 1.30 ms na 0.64 ms sa porastom brzine isklopa sa 2.52 m/s na 4.65 m/s. Kritično vrijeme difuzije luka raste sa porastom promjera kontakata za istu brzinu isklopa.

Ključne riječi: Ponašanje razvoja luka, kritično vrijeme difuzije luka, mehanizam elektromagnetne repulzije, brzi vakumski prekidač, prekidanje struje kratkog spoja, minimalno trajanje luka

INTRODUCTION

Vacuum circuit breakers with advantages of environmental friendliness, being maintenance-free, high reliability, have occupied the medium voltage circuit breaker market and are gradually developing to the high voltage and ultra-high voltage field [1]–[3]. The success of breaking short circuit current for vacuum circuit breakers is mainly determined by the competition between the dielectric recovery and the transient recovery voltage in the post-arc stage after the short circuit current zero [4]. When the post-arc dielectric recovery is faster than the transient recovery voltage, the breakdown will not occur, on the contrary, the occurrence of a breakdown means breaking fails. The post-arc dielectric recovery depends mainly on the initial

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post-arc conditions such as residual plasma density and metal vapor density between contacts, the temperature of the contact surface, which are caused by arc evolution behaviour in arcing process [5], [6]. Therefore, many researchers focus on the arc behaviour of vacuum circuit breakers.

S.Yanabu et al. [7] proposed the coil-type axial magnetic contact that produced an axial magnetic field when an arc current flows through it, which compels the vacuum arc to diffuse. Wang et al. [8], [9] studied the stable and transient vacuum arc characteristics by establishing an MHD simulation model. Sun et al. and Yu et al. [10], [11] used butt contacts to study the influence of travel curve on the evolution of anode discharge mode, and found that a high initial opening velocity is beneficial to the transition of the intense arc mode to the diffusion arc mode, while a slow average velocity can help maintain the magnetic field strength at a large contact gap so that the arc is kept in the diffuse arc mode. Yao et al. [12] quantitatively determined the relationship of opening velocity and transition moment of anode discharge mode and designed a travel curve for a 126 kV vacuum circuit breaker. Jia et al. [13], [14] studied the motion characteristics of cathode spots under different conditions such as arc current, initial arc position and magnetic field strength. Liu et al. [15], [16] estimated critical AMF to prevent anode spots in vacuum interrupters considering the effect of the contact diameter, the arc extinguishing contact gap, and the contact materials. These studies have vital roles in promoting the development and progress of vacuum circuit breakers.

At present, the application of electromagnetic repulsion mechanisms brings new opportunities to the development of vacuum circuit breakers. As the electromagnetic repulsion mechanism has a high opening velocity (up to 2 m/s-10 m/s), a short opening time (less than 1 ms) and a low scattering of opening time (less than 50 us), fast vacuum circuit breakers equipped with the electromagnetic repulsion actuator are widely used in various electric power equipment including DC circuit breaker, superconducting fault current limiter and hybrid current-limiting circuit breaker [17]–[20]. Furthermore, controlled switching technology operating fast vacuum circuit breakers contributes to that the short-circuit fault can be accurately cleared with the minimum arcing time, which lessens the contact erosion and greatly improves the electrical life of the circuit breakers [21]. However, the arc evolution behaviour of fast vacuum circuit breakers, especially the arc evolution behaviour under the minimum arcing time, has not been reported.

The objective of the paper is to determine the arc evolution behaviour of fast vacuum circuit breakers with a minimum arcing time. A 40.5 kV fast vacuum circuit breaker prototype, driven by an electromagnetic repulsion mechanism, was built up. Its average opening velocity can be adjusted from 2.5 m/s to 4.7 m/s. The arc evolution behaviour was being observed by a high-speed camera under different opening velocities and different contact diameters. This research would help to better understand the current interruption mechanism of fast vacuum circuit breakers with the minimum arcing time.

1. EXPERIMENTAL SETUP

1.1. Experimental equipment

1.1.1. The 40.5 kV fast vacuum circuit breaker

Figure 1 shows a 40.5 kV fast vacuum circuit breaker driven by a high-speed electromagnetic repulsion mechanism, which was used to investigate the arc evolution behaviour of fast breaking short circuit current. From the top to the bottom, the fast vacuum circuit breaker included a 40.5 kV vacuum interrupter (VI), an insulation pole, a spring unit, an electromagnetic repulsion mechanism and an oil damper. The average opening velocity can be adjusted by changing the voltage of the pre-charged capacitor bank from 400 V to 700 V. The average opening velocity was defined as the average opening velocity of the stroke from 0 mm to 10 mm, and the measured displacement under the pre-charged voltage of 400, 500, 600 and 700 V is shown in Figure 2. Each displacement curve and opening time were measured, and all measured results are shown in Table I. The average opening velocity is 2.52, 3.53, 4.65 and 5.51 m/s respectively under pre-charged voltage of 400, 500, 600 and 700 V. Furthermore, the opening time of the fast vacuum circuit breaker is less than 1.1 ms, and the scattering of opening time is less than 50 us. The opening time is defined as the time from triggering to contact separation. In the drawn arc experiment, the evolution of arc evolution behaviour at three velocities, namely 2.52, 3.53 and 4.65 m/s, is studied.

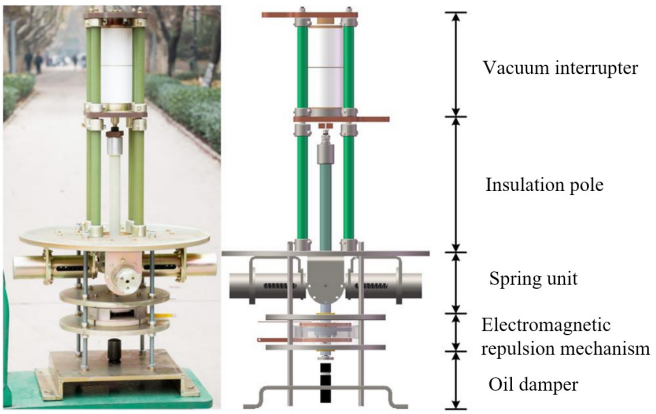

Figure 1: The structure of the designed 40.5 kV fast vacuum circuit breaker

Table I: The results of opening velocity characteristics

Pre-charged voltage	Opening velocity	Opening time	Scattering of opening time
400 V	2.51 m/s	1.02 ms	40 us
500 V	3.52 m/s	0.94 ms	40 us
600 V	4.71 m/s	0.88 ms	40 us
700 V	5.51 m/s	0.82 ms	30 us

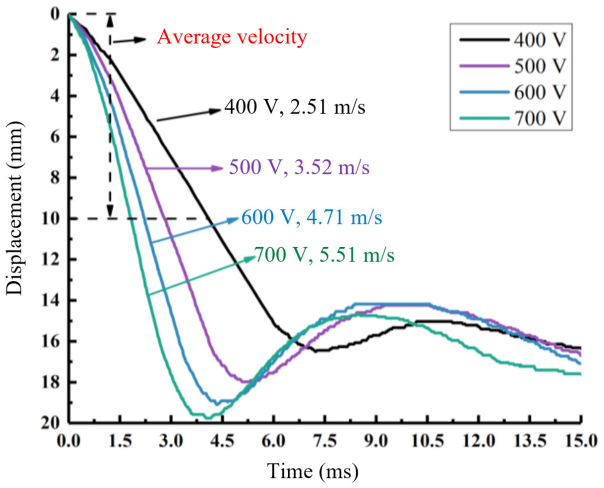

Figure 2: The displacement curves under various charging voltage

1.1.2. The glass envelope vacuum interrupter

The fast vacuum circuit breaker with glass envelope vacuum interrupter was used as experimental equipment to perform the drawn arc experiment. The arc evolution behaviour was observed through the glass envelope. A pair of CuCr50 (Cr 50 wt%) cup-type axial magnetic field (AMF) contacts were equipped in the glass envelope vacuum interrupter, which is shown in Figure 3. To study the influence of contact diameter on arc evolution, three contacts with diameters of Φ50 mm,Φ58 mm and Φ65mm, as shown in Figure 4, are arranged in glass envelope vacuum interrupter respectively.



Figure 3: The structure of the glass envelope vacuum interrupter

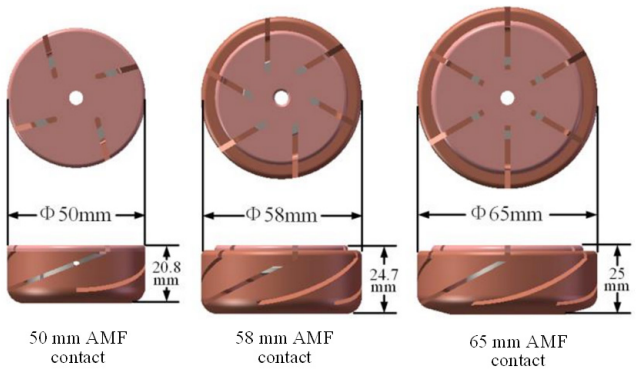

Figure 4: Three kinds of cup-type AMF contacts used in the experiment

1.2. Experimental circuit

The arrangement of the drawn arc experimental circuit is shown in Figure 5. An L-C discharge circuit composed of a 55760 μF capacitor bank and 187.5 mH reactor is used to generate a sinusoidal current of 49.2 Hz near the power frequency. The experimental current is set to 31.5 kA (rms). When the drawn arc experiment started, the main circuit breaker CB1 changed from opening state to closing state, and the fast vacuum circuit breaker operated opening to produce an arc. The evolution of the anode discharge mode was observed using a Phantom high-speed camera CCD. The camera shooting rate was 33333 frames /s, the exposure time was 2 ms, and the aperture value was 4. The arc voltage was measured by a voltage divider and the arc current was measured by a Rogowski coil. During the experiment, the arcing time was adjusted from 2.0 ms to 0.2 ms, stepped by 0.1 ms. In order to adjust the arcing time accurately in the experiment, an arcing time control system was designed specially. The arcing time control system detected the current flowing through the test object using the Rogowski coil, then sent an opening signal to the test object after a settable delay time to gain an expected arcing time. The arcing time control system can adjust the arcing time with the accuracy of 0.1 ms.

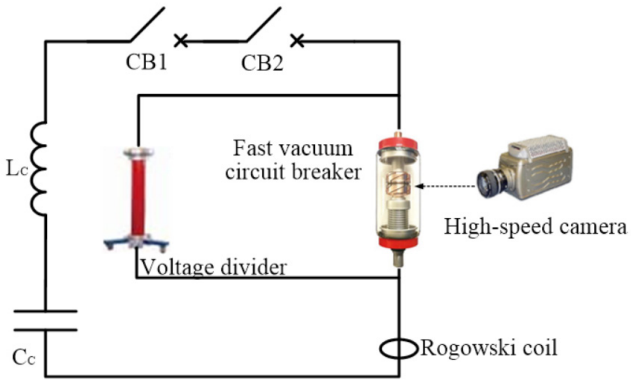

Figure 5: Arrangement of drawn arc experimental circuit

2. EXPERIMENTAL RESULT

2.1. Arc evolution behaviour of fast breaking short circuit current

Figure 6 shows the typical arc current and arc voltage waveform in drawn experiment. The peak of the arc current is 46 kA, and the arc voltage is about 20V. The arcing time can be determined, which is 0.9 ms.

Figure 7 shows the arc evolution behaviour in vacuum interrupter with Φ58 mm AMF contacts under the condition that the average opening velocity is 2.52 m/s and the arcing time is 1.46 ms. In Figure 6, the top contact is the cathode contact, the bottom contact is the anode contact, and the dotted line approximately marks the outline of the moveable and fixed contacts. The current zero is defined as the time zero, and any moment during the arcing process is expressed as a negative instant.

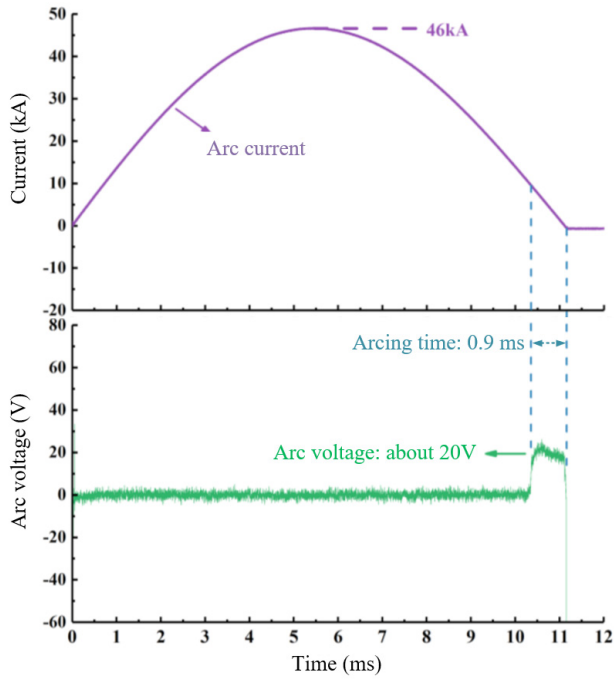

Figure 6: The typical arc current and arc voltage waveform

The instantaneous value of arc current at the arc initiation moment (-1.46 ms) is about 18.1 kA. The metal vapor density at the arc initiation position shall be extremely high, and the arc gathers in a small range near the arc initiation position, that is arc concentrated area, showing local bright spots. At this time, it is an intense mode arc. At -1.17 ms, cathode spots were separating from the arc concentrated area, and then the rapid expansion of the arc range occurred from -1.08 ms. The arc diffuses gradually with the movement of cathode spots, and the brightness of the arc concentrated area decreases correspondingly. The whole diffusion process lasts about 0.36 ms, and after that, the arc diameter reaches the maximum at -0.81 ms. Thereafter, the arc range does not expand further and the arc presents a relatively stable diffuse mode. With the further decrease of arc current, the arc brightness also decreases. Due to the effect of AMF, the arc does not further diffuse to the whole contact surface but gradually weakens. During this process, cathode spots can be observed until the arc is extinguished at the current zero. An important characteristic in the arc evolution behaviour is that the intense mode arc enters a rapid diffusion process after the cathode spots appeared to separate on the contact surface.

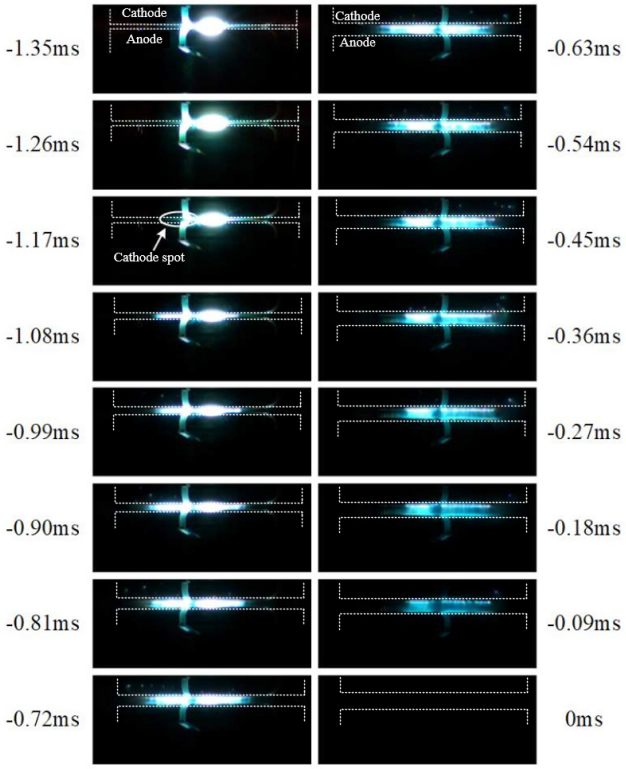

Figure 7: Arc evolution behaviour of Φ58 mm contact under 2.52 m/s and 1.46 ms

Figure 8 shows the arc evolution behaviour under the condition that the average opening velocity is 2.52 m/s and the arcing time is 1.15 ms. The instantaneous value of arc current at the arc initiation moment is about 14.1 kA. At about 0.3 ms after arc initiation moment, the separated cathode spots occurred and an obvious arc diffusion process could be observed starting from -0.84 ms. After about 0.36 ms, the arc diameter reached its maximum value at -0.48 ms. Thereafter, the arc is gradually extinguished with the decrease of arc current. The cathode spots on the cathode surface can be observed during the whole process from the arc diffusion to the arc extinguishment.

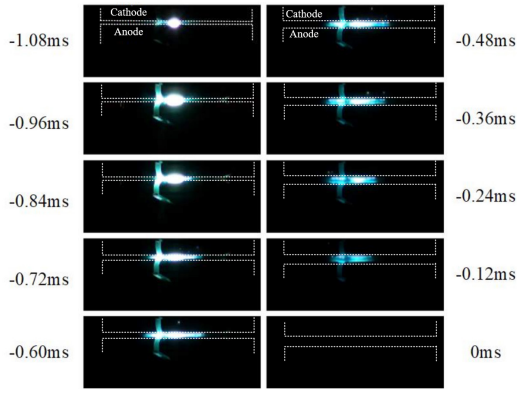

Figure 8: Arc evolution behaviour of Φ58 mm contact under 2.52 m/s and 1.15 ms

Figure 9 shows the arc evolution behaviour under the condition that the average opening velocity is 2.52 m/s and the arcing time is 0.3 ms. The instantaneous value of arc current at arc initiation moment is about 3.8 kA. Because the arcing time is too short, the arc did not evolve into diffuse arc mode before the current zero. During the whole arcing process, the arc is kept in intense arc mode, and no separated cathode spots appear on the cathode surface.

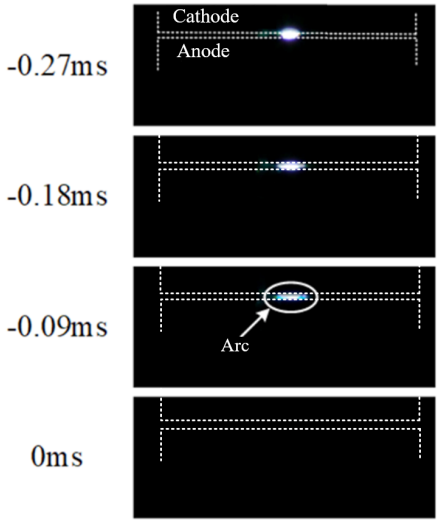

Figure 9: Arc evolution behaviour of Φ58 mm contact under 2.52 m/s and 0.3 ms

As can be seen from Figure 7 to Figure 9, the vacuum arc appears as an intense mode for a period after arc initiation. Thereafter, separated cathode spots appear near the arc concentrated area. After that, the arc diffuses with a movement of cathode spots, and the brightness of the arc concentrated area decreases gradually. The arc diffusion process also takes a certain time. If the arcing time is shortened, there would be no separated cathode spots appearing on the cathode surface, and the arc tends to be extinguished at current zero without diffusion occurring, which is shown in Figure 9.

2.2. Influence of average opening velocity on arc diffusion

The two columns of arc images in Figure 10 show the arc evolution behaviour of *Φ*58 mm AMF contacts at two average opening velocities of 2.52 m/s and 4.65 m/s, respectively. The arcing time of the two experiments is similar (1.88 ms and 1.92 ms), and the average opening velocities are 2.52 m/s and 4.65 m/s, respectively. Each row in Figure 10 represents arc images at the same time before the current zero. As can be seen from the comparison of the left and right arc images, when the average opening velocity is 2.52 m/s, the cathode spots separate from the arc concentrated area at -1.2 ms. However, when the average opening velocity is 4.65 m/s, the instant for the cathode spots to separate from arc concentrated area is advanced to -1.5 ms. In addition, when the average opening velocity is faster, the arc diffusion velocity is faster, the arc diameter before the current zero is larger, and the arc brightness is significantly lower, which indicates that the erosion of the contact surface is lighter. Therefore, a higher average opening velocity is desired.

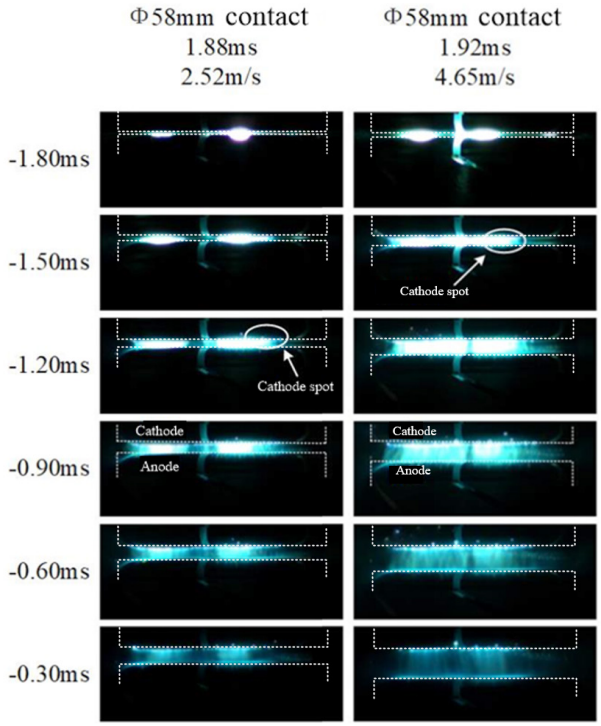

Figure 10: Influence of average opening velocity on arc diffusion

From the arc evolution behaviour of breaking short circuit current with the minimum arcing time, the separation of cathode spots indicates that the arc begins rapid diffusion. Therefore, a critical arc diffusion time is defined as the duration from the instant of contact separation to the appearance of separated cathode spots. The relationship between the critical arc diffusion time of the *Φ*58 mm AMF contact and the average opening velocity is shown in Figure 11. In Figure 11, '○' represents the separated cathode spots observed on the contact surface before the current zero, and '▲' represents that no cathode spots appear before the current zero. The blue solid line in Figure 11 is the boundary of critical arc diffusion time. For a certain opening

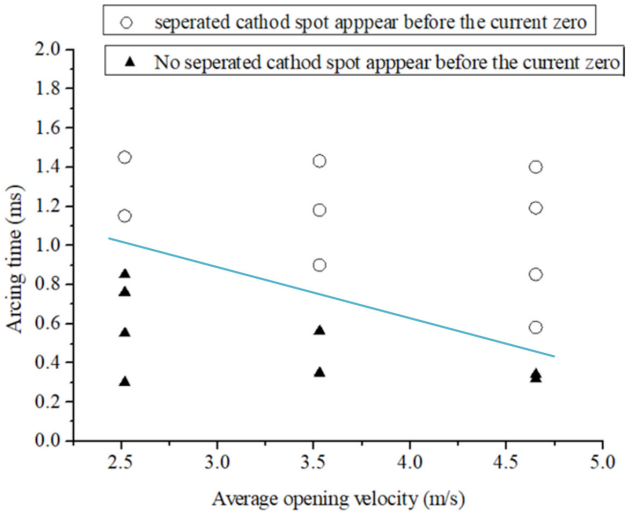

Figure 11: The appearance of separated cathode spots from arc concentrated area before the current zero for Φ58 mm contact

velocity, if the arcing time is lower than the critical arc diffusion time of a certain opening velocity, no cathode spots will separate from the concentrated arc area. Otherwise, the separated cathode spots will appear and the arc diffuse will occur. The critical arc diffusion time decreases from 1.0 ms to 0.58 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s.

2.3. Influence of Contact Diameter on Arc Diffusion

Figure 12 shows arc images in two experiments, which are the arc evolution behaviours with Φ50 mm and Φ65 mm AMF contacts, respectively. In the two experiments, the arcing time is 1.4 ms, and the average opening velocity is about 2.5 m/s. Under this condition, the arc of the Φ50 mm AMF contact appears the separated cathode spot earlier than the arc of the Φ65 mm AMF contact, and the arc of the Φ50 mm AMF contact diffuses earlier than the arc of the Φ65 mm AMF contact. The arc diameter reaches the maximum value in the two experiments at -0.63 ms. At this time, the arc diameters of Φ50 mm and Φ65 mm contacts are about 40 mm and 45 mm, and the ratio of arc diameter to contact surface is 64% and 48%, respectively, which means that the AMF contact with smaller diameter relatively extends the diffuse arc

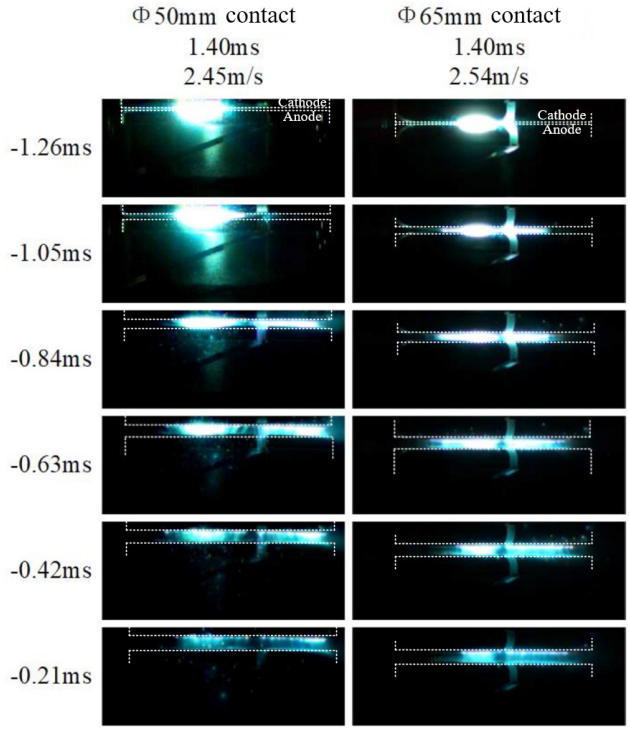

Figure 12: Influence of contact diameter on arc diffusion

wider on the contact.

The relationship between the critical arc diffusion time of three kinds of AMF contacts and the average opening velocity is shown in Figure 13. It can be seen that the critical arc diffusion time of three kinds of contacts linearly decreases with the increase of the average opening velocity. For a Φ50 mm cup-type AMF contact, the critical arc diffusion time decreases from 0.7 ms to 0.46 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s, and the slope of linear decrease is 0.141. What's more, for a Φ58 mm cup-type AMF contact, the critical arc diffusion time decreases from 1.0 ms to 0.58 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s, and the slope of linear decrease is 0.254. For a Φ65 mm cup-type AMF contact, the critical arc diffusion time decreases from 1.3 ms to 0.64 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s, and the slope of linear decrease is 0.446. The critical arc diffusion time of the three contacts is related as follows:

$$T(\Phi 50\text{ mm}) < T(\Phi 58\text{ mm}) < T(\Phi 65\text{ mm})$$

The AMF contacts with a smaller diameter have a lower critical arc diffusion time and a smaller slope of linear decrease.

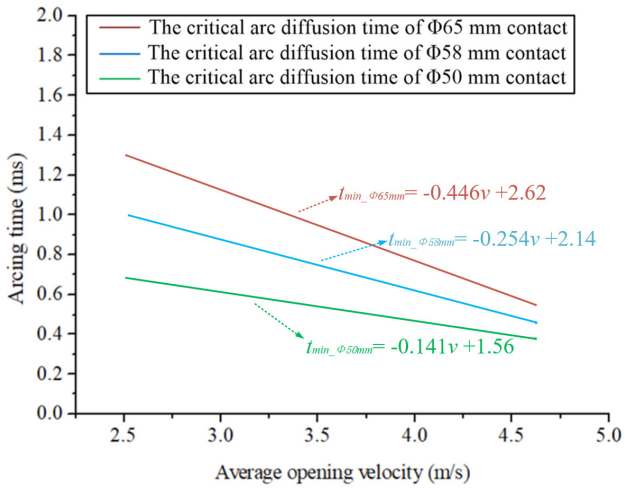

Figure 13: Comparison of critical arc diffusion time for AMF contact

3. DISCUSSION

It can be seen from the opening displacement curves (Figure 2) that the fast vacuum circuit breaker can reach a high velocity after a short acceleration process in the opening process. The higher the average opening velocity is, the larger the instantaneous contact gap is. Figure 14 is a further analysis of the results shown in Figure 10. Each row in Figure 14 represents arc images at the same time before the current zero, and the corresponding instantaneous contact gap of each arc image is marked on the right side of the arc image. It can be seen from Figure 14 that the experiment with a higher average opening velocity has a larger contact gap at the same time, which results in an earlier appearance of separated cathode spots and a faster transition of the vacuum arc from the intense mode to the diffuse mode. As a result, the instantaneous contact gap plays an important role in the arc behaviour evolution of fast breaking short circuit current with a minimum arcing time.

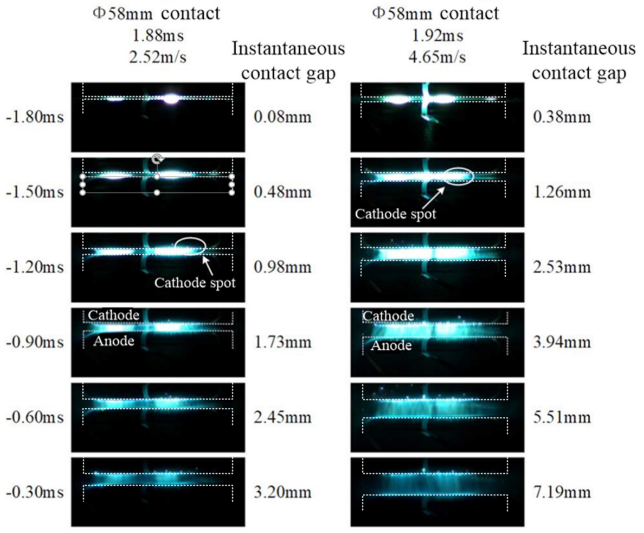

Figure 14: Comparison of critical arc diffusion time for AMF contact

Figure 15 proposes a physical process of the vacuum arc plasma evolution in fast breaking short circuit current with a minimum arcing time. During an extremely short period after the arc initiation, the arc initiation position on the contact surface is the plasma emission source, as shown in Figure 15 (a). After that, arc plasma mainly gathers in a small arc concentrated area near the arc initiation position, and has high plasma density (intense arc), as shown in Figure 15 (b). During this stage, on the one hand, the arc plasma tends to diffuse spontaneously from the high-density region to the low-density region; on the other hand, the arc concentrated area has a high current density, causing that the arc will shrink inward under the action of pinch effect. The two effects tend to be balanced. On the whole, the arc diameter does not increase significantly, and the plasma density remains at a high level. With a decrease of current, the pinch effect of arc plasma is weakened, and some cathode spots can escape from arc concentrated area, as shown in Figure 15 (c). The cathode spots, as the plasma emission source, were released to move freely on the contact surface from the arc concentrated area, which might be under an action of the plasma density gradient. The separation of cathode spots reduces the plasma density and current density of arc concentrated area, which further causes the release of more cathode spots, as shown in Figure 15 (d). As shown in Figure 16, the cathode spots releasement can enter a positive feedback process when the cathode spots separate from the intense arc. In this positive feedback stage, the diameter of the intense arc decreases rapidly, meanwhile, the diffuse arc expands and finally, the whole arc becomes a diffuse arc, as shown in Figure 15 (e). In this case, the erosion of the contact is relatively low. When the diffuse arc reaches a certain range, the cathode spots does not expand further once this phase is reached, then the arc shrinks and finally extinguishes with the gradual decrease of arc current.

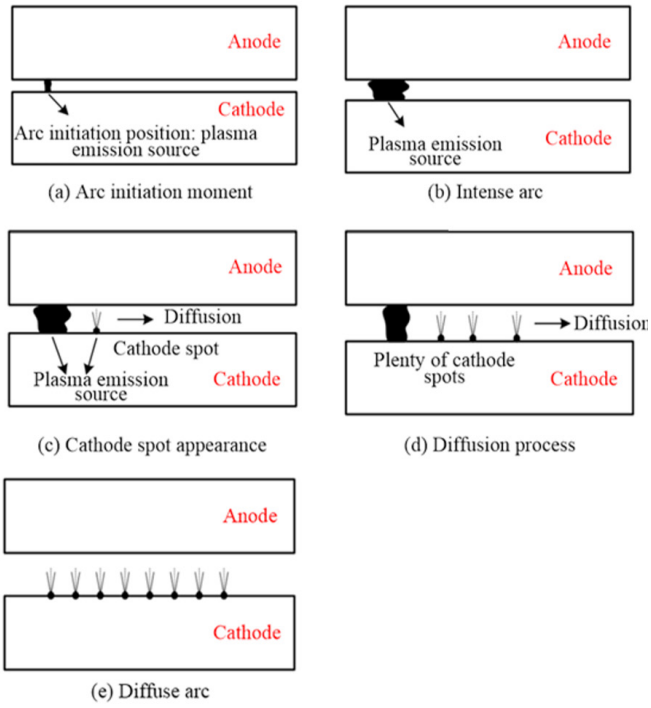

Figure 15: Arc plasma evolution process of fast breaking short circuit current

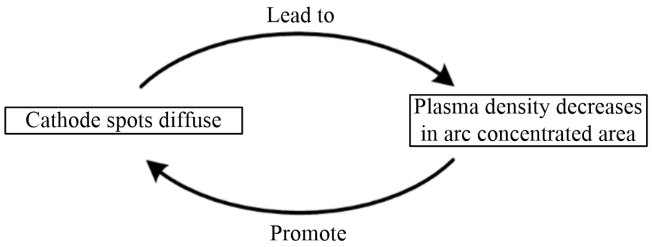

Figure 16: Positive feedback process of arc diffusion after cathode spot separation

4. CONCLUSION

This paper experimentally studies the arc evolution behaviour of a fast vacuum circuit breaker breaking short circuit current with the minimum arcing time. A 40.5 kV fast vacuum circuit breaker with an electromagnetic repulsion mechanism, whose opening velocity can reach a range between 2.52 m/s and 5.51 m/s is designed and developed. Its opening time is less than 1 ms, and the scattering of opening time is less than 50 ms. The influence of opening velocity and contact diameter on arc evolution behaviour has also been studied. The conclusions are as follows:

(1) There is a critical arc diffusion time in the arc evolution behaviour under breaking a short circuit current. When the arcing time is larger than the critical arc diffusion time, separated cathode spots from the intense arc will appear on the cathode surface and the arc will diffuse further rapidly. When the arcing time is lower than the critical arc diffusion time, the cathode spots will not separate and the arc will not become diffuse.

(2) The critical arc diffusion time decreases with the increase of average opening velocity. For a Φ50 mm cup-type AMF contact, the critical arc diffusion time decreases from 0.7 ms to 0.46 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s. For a Φ58 mm cup-type AMF contact, the critical arc diffusion time decreases from 1.0 ms to 0.58 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s. For a Φ65 mm cup-type AMF contact, the critical arc diffusion time decreases from 1.3 ms to 0.64 ms with the increase of the opening velocity from 2.52 m/s to 4.65 m/s.

(3) The cup-type AMF contacts with smaller diameters have lower critical arc diffusion time

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