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Distribution of Cathode Spots in Vacuum Arc Under Nonuniform Axial Magnetic Fields

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Abstract Recent results on the distribution of vacuum arc cathode spots (CSs) in nonuniform axial magnetic field (AMF) are presented. Based on previous studies, we deem that two contrary influences of AMF, inward effect and outward effect, are attributed to CSs distribution. With this notion, we have analyzed the controlling effectiveness of nonuniform AMF on CSs distribution. Experiments were conducted in a detachable vacuum chamber with iron-style AMF electrodes. Images of vacuum arc column and the distribution of CSs were photographed with a high-speed charge coupled device (CCD) camera. Experimental results agreed well with the theoretical analysis.

Keywords: axial magnetic field, cathode spots, vacuum arc

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1 Introduction

Axial magnetic field (AMF) electrodes are widely used in vacuum interrupters since an AMF can keep the vacuum arc in a diffusive mode at high current. Consequently, the current interruption capacity can be enhanced.

Recently, some studies showed that a nonuniform AMF with higher axial magnetic flux density near the contact periphery than that near the center (saddle shaped AMF) can make the arc plasma more uniform than either a uniform AMF or an ordinary bell shaped AMF profile generated by a conventional AMF electrode structure [1∼7]. HOMMA et al [1] reported on saddle shaped AMF electrodes with a new electrodes structure (SADE), which had two equivalent coils with different diameters and opposite current directions. CHALY et al [4] proposed two AMF criterion values, and the approach for generating the saddle shaped AMF was nearly the same to that adopted for SADE [1].

In our previous works [2,3,5∼7], we studied the effect of AMF distribution on the characteristic of vacuum arc by theoretical analysis, simulation, and experiments. The nonuniform AMF was implemented by adding ferromagnetic material (iron) into AMF electrodes. In this paper, further study will be presented on the mechanism of CSs distribution in nonuniform AMF.

To understand the mechanism of CSs distribution in nonuniform AMF, particularly, in saddle shaped AMF, CHALY et al [4] adopted Steenbeck minimum principle. Their investigation showed that the 'magnetic barrier', which is also the saddle shaped AMF, represents an optimum AMF configuration, providing even current distribution and relatively low and stable arc voltage.

Based on some previous investigations, we deem that AMF has two contrary effects, inward effect and outward effect, on CS motion that should be attributed to CSs distribution in nonuniform AMF, particularly, at high current. To verify this notion, we have conducted a series of experiments in a detachable vacuum chamber with iron-style AMF electrodes. The experimental results could be well explained by the theoretical analysis.

2 Theoretical analysis on cathode spots distribution in nonuniform axial magnetic field

The retrograde motion of CS in tangential magnetic field is the most mysterious phenomena of vacuum arc, which is not fully understood yet. In spite of the unclearness of the exact mechanism of CS retrograde motion, based on a substantial amount of theoretical and experimental studies, it is most likely that the retrograde motion of CS is related to the unsymmetrical change of the local environment very near the cathode surface, e.g., the shift of positive space charges [8], or the change of conductivity [9]. In this paper, we do not intend to devote ourselves to the mechanism of CS retrograde motion, but study the CSs distribution in nonuniform AMF based on previous investigations.

FANG [8] investigated the CS retrograde motion speed in a tangential magnetic field. With single CS (arc current up to 60 A) on copper cathode, the experiments showed that the speed of CS retrograde motion increases linearly with the increase of applied tangential magnetic field. By observing the expanding velocity of the CSs ring after triggering the vacuum arc with a relatively high current (up to about 10 kA), SHERMAN et al [10], and AGARWA et al [11] found the same relation between the CS retrograde motion speed and the magnitude of azimuthal magnetic field. It was also found that with the increase of applied AMF, the CS retrograde motion was retarded [11]. It should be noted that the slowdown of CSs retrograde motion, to some extents, represents the decrease of the probability of CS retrograde motion, which may be understood by the incremental CSs number inside the outward expanding CSs ring with the increase of AMF [11]. Since AMF inhibits the outward retrograde motion of CSs in high current, so we call this effect, phenomenally, the 'inward effect'.

At relatively high current, it was also found that the speed of CS retrograde motion saturated at relatively strong azimuthal magnetic field, i.e., with small radius of expanding CSs ring [10,11]. This phenomenon was explained through the finite heating speed of an emission site by a CS [10,11]. However, from another point of view, this phenomenon can be explained by the concentration of plasma (neutral or ionized atoms) near the arc axis at cathode surface, which encourages new CS to reignite inward with larger probability than outward reignition [12]. The concentration of plasma near central cathode surface may come from anode (secondary plasma [12]) due to localized increase of thermal load near anode center, which is caused by the small radius of CSs ring and the constriction of arc column near anode surface. It should be noted that the plasma near central cathode surface could also originate from the cathode, directly, due to the evaporation of cathode material and observed plasma constriction near cathode surface [13]. With above analysis, the linear relation between the speed of single CS retrograde motion and applied tangential magnetic field without saturation (tangential magnetic field up to 120 mT) [8] could be explained by slight activity of both anode and cathode.

Due to the well-known collimation effect of AMF, the constriction of arc plasma near anode and cathode can be reduced. Consequently, the probability of outward reignition of new CS would increase. So, we call this effect, phenomenally, the 'outward effect'.

For practical vacuum interrupters, we expect that CSs could make the most of cathode surface, and distribute more uniformly in the region occupied by CSs. Combining above two basic contrary effects of AMF on CS motion, we can analyze the influence of AMF distribution on CSs distribution at high current. We will focus on CSs distribution at quasi-steady state, but not on the expanding process after arc ignition.

The outward effect of AMF requires that the constriction of plasma near anode and cathode should be reduced. In our previous studies [5,7], the effect of AMF distribution on arc column was studied with a magnetohydrodynamic model by assuming either uniform or nonuniform CSs distribution. For non-uniform CSs distribution, the CSs density is assumed higher at cathode center than that at cathode edge according to experimental results. It was found that for resisting the constriction of arc column, the axial magnetic flux density is more important near electrode periphery than that near electrode center. Experiments conducted with iron-style AMF electrodes with different AMF distributions further verified above notion [6]. It was also supported by other studies (e.g., Fig. 8 in Ref. [4]).

Assuming that CSs distribute uniformly on entire cathode surface, the azimuthal magnetic field, driving the outward motion of CSs, should be stronger near cathode periphery than that near cathode center. According to above analysis, the speed and probability of CSs outward motion should be greater near cathode periphery than that near cathode center. So, the inward effect of AMF should be weak near cathode center to prevent more CSs from staying in central region. On the contrary, the inward effect of AMF should be strong near cathode periphery to prevent CSs from moving onto the side surface of cathode, which will raise noise in arc voltage.

From above analysis, we can see that an "optimal" AMF distribution for inward effect should have a saddle shaped profile, which also has relatively fine outward effect.

3 Experimental technique

To verify the notion, we conducted a series of experiments in a detachable vacuum chamber. The internal pressure of the detachable vacuum chamber was maintained below 10^{-4} Pa by continually pumping by a turbo-molecular pump. Arc current was supplied by a capacitor bank connected in series with an inductive reactor to provide sinusoidal current pulse with a frequency of 50 Hz. The current waveform was acquired from a non-inductive shunt.

The vacuum arc was ignited by a trigger spark within a hole at the center of the cathode. Images of arc column and cathode spots were photographed with a CCD camera (Kodak Ektapro High Gain Imager) with an exposure time of 1/6000 s. While photographing the CSs, the camera axis was inclined by about 15° relative to cathode plane. To weaken the influence of the brightness of arc column on the image of CSs, one or two neutral color filters were added in front of the lens at high current, and the aperture was set to the smallest. However, in order to compare different AMF electrodes, an exactly same camera setting was used for all AMF electrodes at same current.

Two pairs of iron-style AMF electrodes were used. Both of the two electrodes have quasi-saddle-shaped AMF distributions [6]. In order to make the compari-

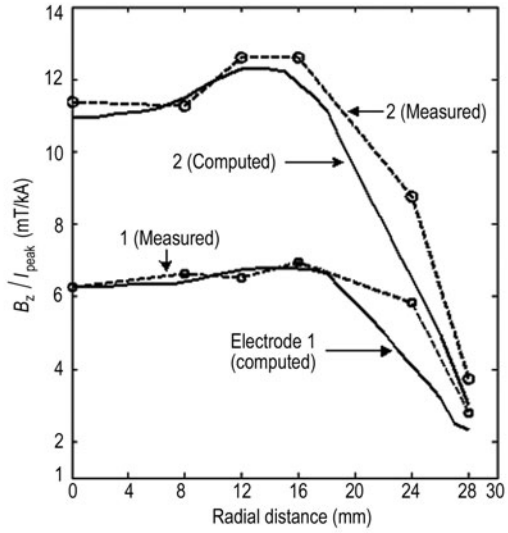

Fig.1 Radial distribution of B_z/I_{peak}; solid lines are the calculated; dashed lines are the measured results

son clearer, we designed two electrodes to have much different overall AMF strength. The AMF distribution was calculated with ANSYS, and validated by measurement. The details of electrodes construction, modeling, and AMF measurement were given previously [6]. The electrodes material and dimension are same to that in previous study [6]. The major parameters are as follows. The diameter of contact plate is 56 mm, the electrodes gap is 10 mm, and the material of contact plate and electrode cup is CuCr25 and OFHC copper, respectively. Fig. 1 shows the calculated and measured distributions of the ratio between the amplitude of the axial magnetic flux density (B_z) and the peak current (I_{peak}) (AC, 50 Hz) in the mid-plane of the inter-electrode gap.

4 Experimental results

Experiments were conducted with the two pairs of iron-style AMF electrodes. The images of arc columns and CSs at I_{peak}= 6.9 kA, 9.4 kA, 12.1 kA, and 18.8 kA, taken 5 ms after the ignition of the arc (i.e., at the peak of current) are shown in Fig. 2, Fig. 3, Fig. 4, and Fig. 5, respectively.

5 Discussions

Based on the above theoretical analysis, the AMF distribution in Fig. 1, and the images of arc columns, we can analyze the mechanism of CSs distribution in different AMF distributions and arc currents.

At a low current of $I_{peak} = 6.9$ kA, since the constriction of arc column is slight (Fig. 2 (a)), the influence of secondary plasma on CSs distribution is weak. Consequently, the outward effect of AMF is not distinct. On the contrary, the inward effect of AMF is prominent, which can be seen clearly from Fig. 2. With electrode 1, the inward effect is relatively weak due to weaker B_z.

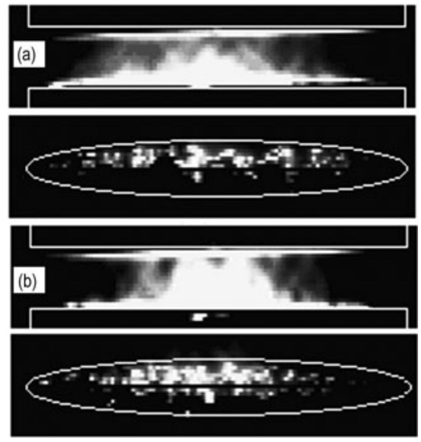

Fig.2 Images of arc column (lower electrode is cathode) and cathode spots taken 5 ms after arc ignition, $I_{peak} = 6.9$ kA; (a) electrode 1; (b) electrode 2

As a result, CSs spread uniformly on cathode surface with slight concentration near cathode center. Whereas, with electrode 2, the inward effect is stronger, particularly in central region. So, some CSs concentrate in central region. Therefore, the arc column burns mainly in the region where CSs concentrate.

Above CSs local concentration phenomenally resembles the cathode spot group formation (CSGF) [12,14], which occurred in the case of short arc, e.g., electrode gap (g) less than 2 mm [14], and g less than 4 mm [12]. Chaly and co-workers attributed CSGF to the influence of secondary plasma, particularly in short arc. However, in present investigation, it is obvious that this phenomenon is also bound up with the inward effect of AMF, even though the arc is relatively long (g = 10 mm).

At a relatively high current, $I_{peak} = 9.4$ kA and $I_{peak} = 12.1$ kA, the arc column tends to constrict towards anode. With electrode 1, the constriction is more severe than that with electrode 2 due to its weaker AMF, particularly near the periphery of arc column, which is more important than AMF strength in central region according to our previous researches [5~7]. From Fig. 3 ~4, it can be found that with electrode 1, CSs tend to gather in central region due to the effect of secondary plasma. Whereas, with electrode 2, the arc column looks more 'straight' than that with electrode 1, i.e., AMF resists the constriction of arc column, effectively. Consequently, the outward effect works better than in electrode 1 case. So, CSs concentration is still mainly governed by the inward effect.

The outward effect of AMF is more distinct at much higher current. From Fig. 5 (a), we can see that CSs concentrate in smaller central region due to severe constriction of arc column. In this case, the outward effect is not strong enough. On the contrary, electrode 2, with stronger outward effect, still keeps a larger CSs concentration region.

From above discussion, we can see that the theoretical analysis agrees well with the experimental results, i.e., CSs motion and distribution is affected by the com-

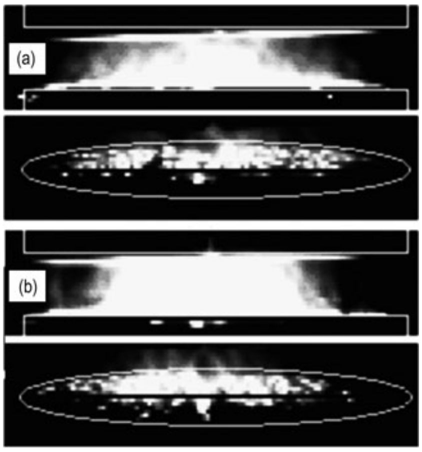

Fig.3 Images of arc column (lower electrode is cathode) and cathode spots taken 5 ms after arc ignition, $I_{\rm peak} = 9.4$ kA; (a) electrode 1; (b) electrode 2

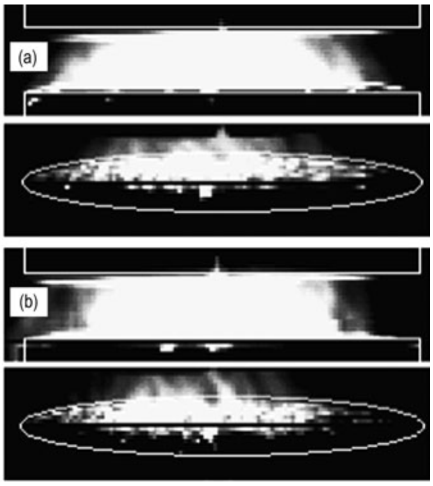

Fig.4 Images of arc column (lower electrode is cathode) and cathode spots taken 5 ms after arc ignition, $I_{\rm peak} = 12.1$ kA; (a): electrode 1; (b): electrode 2

bined effect of outward effect and inward effect of AMF. This notion can provide a way to design more 'optimal' AMF distribution. For example, assuming we can make central $B_{\rm z}$ in electrode 2 weaker, and make peripheral $B_{\rm z}$ stronger, i.e., the AMF profile tends to be saddle shaped, then the inward effect could be weakened, and the outward effect could be strengthened. Consequently, it can be expected that CSs could distribute more uniformly.

6 Conclusion

Both theoretical analysis and experimental results show that the motion and distribution of vacuum arc cathode spots is significantly affected by outward effect and inward effect of AMF. At a low current, while the constriction of arc column is not severe, the inward effect dominates the CSs distribution. With the increase of arc current, the outward effect gets more and more significant. To resist the inward effect of AMF in central region without weakening the outward effect in periphery region, the saddle shaped AMF is favorable. It is also found that the phenomenon of cathode spots group formation may occurs not only in short arc due to the effect of secondary plasma, but also in long arc under strong AMF due to inward effect.

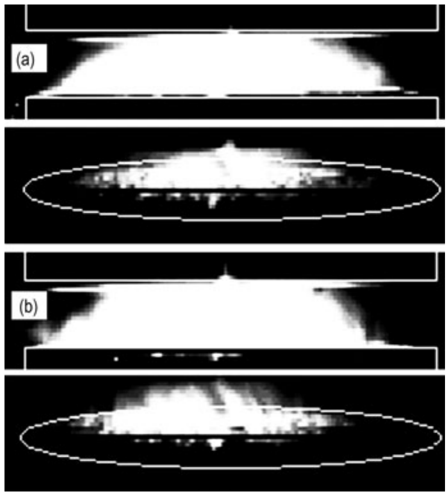

Fig.5 Images of arc column (lower electrode is cathode) and cathode spots taken 5 ms after arc ignition, $I_{\rm peak} = 18.8$ kA; (a): electrode 1; (b): electrode 2

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