An Opening Displacement Characteristic Determined by High-Current Anode Phenomena of Vacuum Interrupter

Liqiong Sun, Li Yu, Zhiyuan Liu , Jianhua Wang and Yingsan Geng
State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an 710049, China

Abstract- **A vacuum interrupter reaches its interruption limit once high-current anode phenomena occur. It is well-known that contact diameter, contact material, and magnetic field have a significant influence on high-current anode phenomena formation. However, an opening displacement characteristic of movable contact is another contribution for an anode spot formation. The objective of this paper is to propose an opening displacement characteristic for a vacuum interrupter to avoid a formation of high-current anode phenomena. The anode phenomena were observed by using high speed CCD camera. The vacuum interrupters were used in the experiments, which had a glass envelope and there was no stainless shield installed. The diameters of butt type contacts were 12 mm and 25 mm, respectively. The average opening velocities during 10ms after contacts separated were ranged from 1.1m/s to 2.0m/s. And arcing time was adjusted from 2ms to 10ms with a fixed velocity and peak arc current. The results showed that in an anode diagram for each vacuum interrupter, an arcing curve can be obtained, which avoids the regions of intense arc mode and anode spot mode. And this arcing curve corresponds to an opening displacement curve of vacuum interrupter. With the proposed opening displacement curve, high-current anode phenomena will not occur, which has a positive impact on the interrupting performance of the vacuum interrupter.**

I. INTRODUCTION

If an arc current passing through a vacuum arc reaches a high value, one or several footpoints or anode spots will form on the anode surface of a vacuum interrupter. At present, the formation of anode spot is recognized as a main factor for a vacuum interrupter reaching its interrupting limit [1, 2]. When a vacuum interrupter is used to switch an AC circuit, the region of anode surface when anode spot formed is a source of particles and metal vapor emission to the switching gap even at times several milliseconds after current zero. When an appreciable recovery voltage appears across the gap, there are enough metal vapors present to cause reignition and failure.

Another possible reason of recovery failure is because the anode spot is so hot that it cools so slowly after current zero. And the anode spot site is still kept a liquid surface layer at current zero. As the recovery voltage increases it produces a strong electric field. The liquid layer can be distorted to create projections which are potential sites for high voltage breakdown. Thus it also leads to an interruption failure [3]. Thus, the main limitation for the interruption ability of vacuum interrupter is closely related with the presence before current zero of the high-current anode phenomena.

For improving breaking capability of vacuum interrupters, much research work has been done on understanding the anode spot formation. Boxman et al. [4] proposed a critical current I_{as} for anode spot formation, and I_{as} will be determined by the relationship between the interelectrode gap and the anode diameter. Miller [5, 6] presented that the critical current I_{as} will be determined by the relationship between contact gap and contact diameter (especially the ratio of contact diameter and contact gap D/g), contact material, current waveform, etc. Another technology for avoiding anode spot formation is that of using an axial magnetic field to keep the vacuum arc diffuse. Yanabu and Kaneko [7, 8] showed that not only an axial magnetic field will restrain arc column constriction, but also electric arcs will distribution in anode surface uniformly.

The opening displacement characteristic has much influence on anode phenomena. E. Kenado et al showed that the interrupting performance of a chamber will be influenced by the initial opening velocity. The fast initial opening velocity can reduce contact erosion and improve the capability of the chamber effectively [9]. Mitchell's results showed that the critical current I_{as} of transition from diffuse arc to concentration arc will be decreased with an increase of a gap [10].

However, little work has been done to avoid the anode spot formation according to an whole opening displacement characteristic of a movable contact in vacuum interrupters. The objective of this paper is to propose an opening displacement characteristic for a vacuum interrupter to avoid a formation of high-current anode phenomena.

II. EXPERIMENTAL SETUP

The test vacuum interrupter was shown in Fig. 1. In order

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to observe the vacuum arcs, the envelope of the vacuum interrupter is made of glass without stainless-steel shield. Therefore, the anode phenomena can be observed by a high-speed photography. We prepared 3 vacuum interrupters of 12 mm contact diameter and 2 vacuum interrupters of 25 mm contact diameter and the contact material was CuCr25 (25% by weight of Cr).

Experiments were conducted using the apparatus shown schematically in Fig. 2. The test vacuum interrupter was operated by a permanent magnet operating mechanism. Tests were conducted by charging capacitor banks to an appropriate voltage, and initiating a power frequency current (50 Hz) by passing through reactors (LC discharging circuit). The discharging current was controlled by the charging voltage of the capacitor banks. Arc voltage was measured by means of a Tektronix high voltage probe 6015A (1000:1). Arc current was measured by a shunt of 90μΩ.

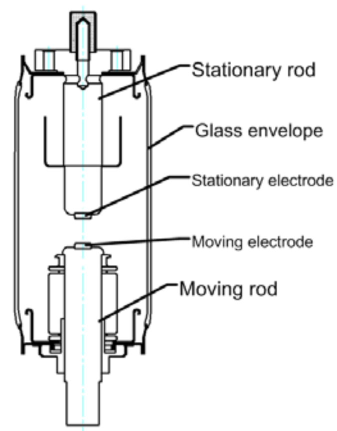

Fig. 1 Test vacuum interrupter

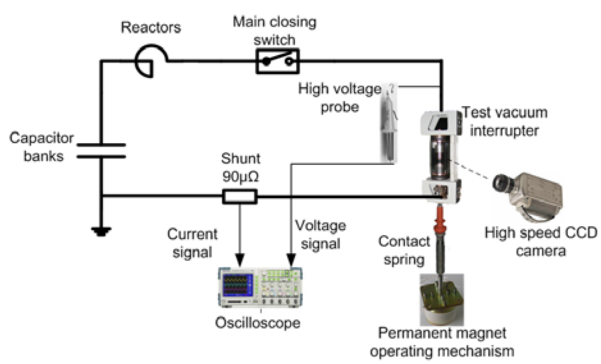

Fig 2 Experimental circuit

We observed the vacuum arc phenomena with a high-speed charge-coupled device (CCD) video camera Phantom V10 at a speed of 10 frames per millisecond. Exposure time of the individual frames was 2 μs. The high speed CCD camera kept focusing on the upper electrode (stationary electrode) which is the anode. The contact gap between the electrodes was determined by comparing with the size of contact whose contact diameter was 12 mm or 25 mm in each frame of camera movie. And the diameter of anode spots can also be determined by this method. A frame where a first bright spot appeared was identified as the beginning of arcing and it was correlated to the instant of a voltage jump of 20 V on the arc voltage record. Thus, the correlation among the anode phenomena, arcing current, arcing time and contact gap can be obtained.

In order to investigate the relationship between the anode discharge modes diagram and the opening displacement characteristic, two opening velocities (1.1 m/s and 2.0 m/s)

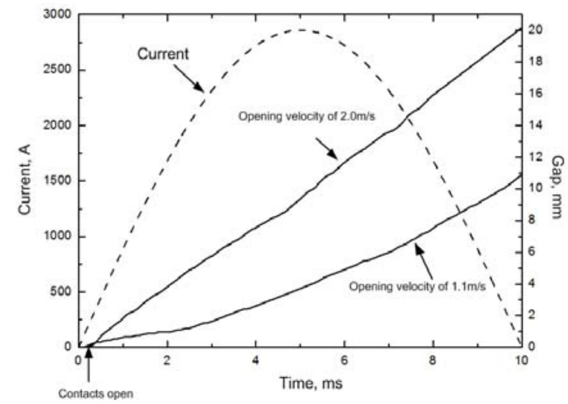

Fig. 3 Typical arc current and electrode gaps with opening velocity 2.0 m/s and 1.1 m/s

were adopted to compare their influence on the high-current anode phenomena. The opening velocity can be adjusted by adjusting

a contact spring stoke from 1 mm to 9 mm. The opening velocity was defined as an average velocity during 10 ms after contact separation as shown in Fig. 3.

As shown in Fig.4, while the electrodes kept closing in the first three half-waves of the 50 Hz power frequency current, the movable electrode was electronically controlled to be separated within the fourth half-wave of the initiated current. And the arcing time can be adjusted in the range from 2ms to 9ms in each experiment when the arc extinguished at the first arc current zero point. In this case, the anode discharge modes diagrams of two different opening velocities can be

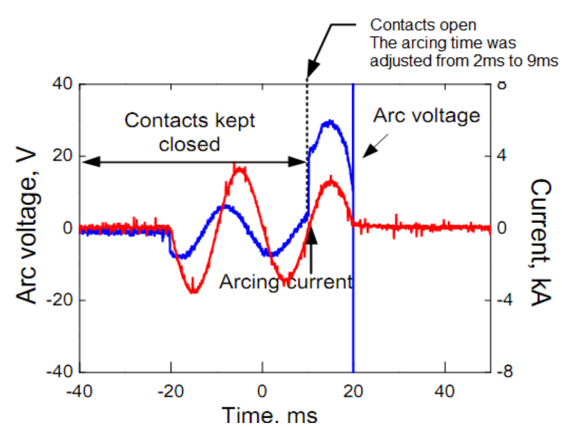

Fig. 4 Contacts open at the fourth half-wave (the stationary electrode is an anode)

obtained.

III. Results

A. Anode discharge diagram

Based on the anode phenomena definition by Miller [1, 5, 6], we distinguished four anode discharge modes in our experiments: diffuse arc mode, footpoint mode, anode spot mode and intense arc mode. Since for one arcing sequence, each change in anode discharge modes is associated with a specific arc current and contact gap value and is indicated as one point on the characteristics. Then the instantaneous arc current and contact gap can be recorded. The anode discharge diagram of a vacuum interrupter with CuCr25 contact material and 12mm contact diameter was established as shown in Fig. 5. Symbol "▲" represented a change between a "diffuse arc" and a "footpoint" anode discharge modes. Symbol "●" represented a change between a "footpoint" and an "anode spot" anode discharge modes. And symbol "■"represented a change between an "intense arc" and the other three anode discharge modes. The symbols "▲, ●, ■" were in a condition that the average opening velocity was 1.1m/s. In addition, the symbols "△, □, ○"represented anode discharge modes transition with an average opening velocity of 2.0m/s. With a large number of transition points between anode discharge modes transition, we can establish boundaries between regions of different anode discharge modes in a gap-current diagram. And an anode discharge modes diagram for a CuCr25 contact material with 25mm diameters vacuum interrupter was shown in Fig.6.

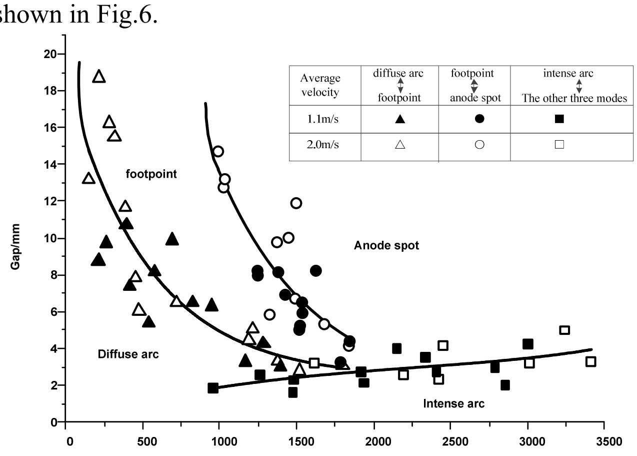

Fig. 5 Anode discharge distribution with crystallite CuCr25, contact diameter 12mm

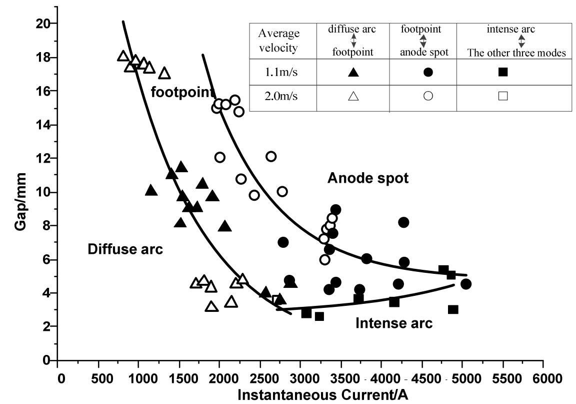

Fig. 6 Anode discharge distribution with crystallite CuCr25, contact diameter 25mm

B. Relationship between an anode discharge diagram and an opening displacement characteristic

It is valid for arcs between 12mm diameter vacuum interrupter separated during a 50Hz half-cycle of current at opening velocities of 1.1m/s and 2.0m/s. No consistent change in the anode discharge modes diagrams between 1.1m/s and 2.0m/s. It is shown that the opening velocity had a little influence on the anode modes diagram. Consequently, we expected that these exist a specific anode discharge diagram for a given vacuum chamber. And it didn't change according to the opening velocity of electrode.

An arcing curve that avoids anode spot mode and intense arc mode occurring is proposed in an anode discharge diagram. For example, an anode discharge diagram for vacuum interrupter with 12mm diameter butt type electrodes of CuCr25 contact material is shown in Fig.7. We suppose that this type vacuum interrupter is used to interrupt an arc current of 1650A (peak value). Then three different opening displacement characteristics are shown with a same arcing time of 9.5ms. When the electrodes separate with an average velocity 2.0m/s (as represented by a dash line), a diffuse arc mode formed initially. Thereafter, at a contact gap of 4mm and arc current of 984A (instantaneous value), a footpoint formed. And even further, the vacuum arc changes into an anode spot mode when the arc current reaches 1490A (instantaneous value) and the contact gap reaches 6.7mm. When the current fell below a value of 1006A, the anode spot converted into footpoint with a contact gap of 15mm. And the footpoint disappears when an arc current is lower than 214A (instantaneous value) and a contact gap reaches 18.7mm. Hereby, the vacuum arc becomes a diffuse arc.

When the contacts separate with an average opening velocity 1.1m/s (as represented by a dash dot line), the arcing sequence becomes better because an anode spot mode disappears. In such a case, an intense arc mode is formed at first. At a gap of 2.4mm, the intense arc transfers into a footpoint mode when an arc current reaches a value of 1528A (instantaneous value). And the footpoint mode disappears when the arc current falls at 215A (instantaneous value) and contact gap reaches 9.6mm. After that, a diffuse vacuum arc forms.

The third opening characteristic was represented by a solid curve, with which the arcing sequence becomes even better because both an anode spot arc mode and an intense arc mode are avoided. A diffuse arc mode was formed at the beginning. Then a footpoint formed when the arc current reaches 1469A (instantaneous value) and the contact gap reaches 3.49mm. As the arc current increases, the peak arc current value locates in a footpoint mode region. When the arc current falls to 606A (instantaneous value) and the contact gap reaches 7.7mm, anode phenomena disappears. The remained vacuum arc is a diffuse arc mode.

It is found that with an opening velocity 2.0m/s, arcing curve will pass through an anode spot region partly. While with an opening velocity 1.1m/s, the vacuum interrupter will suffer an intense arc mode when the contact gap is low. Both an anode spot and an intense arc will overheat the anode surface of the vacuum interrupter which has a negative impact on current interruption. Therefore, we propose the third arcing curve to avoid a region of an intense arc mode and an anode spot mode which can be obtained based on an anode discharge diagram. And this arcing curve will have a positive impact on a high-current interruption for vacuum interrupters.

Three opening displacement characteristic curves are shown in Fig.8, which correspond to the three arcing sequences in Fig. 7. It was found that the duration of an anode spot is from 3.6ms to 7.8ms when an average opening velocity is 2.0m/s, and overall the anode is active from 1.9ms to 9.5ms. When an average opening velocity is 1.1m/s, the duration of an intense arc mode is from 0ms to 3.8ms, and anode is not active until a footpoint extinguishes at 9.3ms. Moreover, the proposed opening displacement characteristic curve passes through only a footpoint mode, and the duration of the footpoint mode is from 4.1ms to 7.8ms. A high initial velocity at the beginning of contacts separation can keep the vacuum arc away from a region of an intense arc mode.

IV. CONCLUSION

Experiment results show that opening velocities has little influence on an anode discharge mode diagram. Thus, an anode discharge mode diagram can be drawn for a kind of vacuum interrupter according to anode mode observation experiments. Based on the anode discharge mode diagram, an opening displacement characteristic can be proposed to avoid an anode spot region and an intense arc mode region, which will have a positive impact on a high-current interruption in vacuum.

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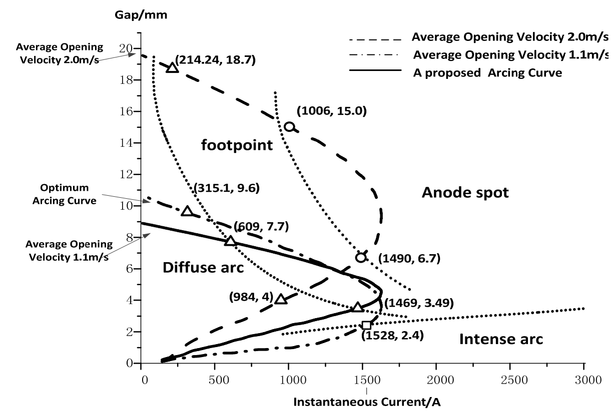

Fig. 7 Anode discharge mode diagram with three opening displacement characteristics

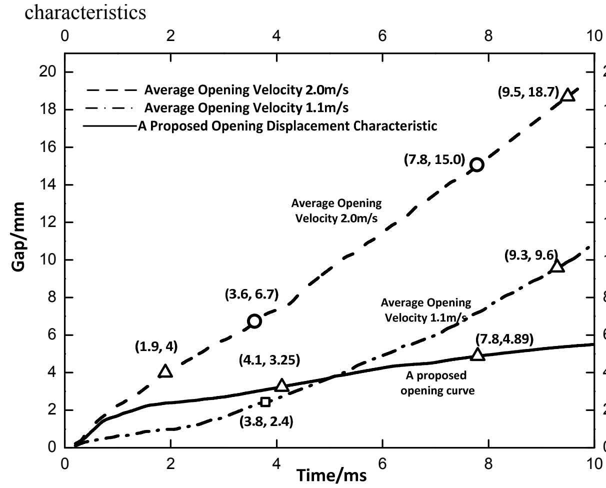

Fig. 8 Three opening displacement characteristics with different arcing curves

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Email of Author: liuzy@mail.xjtu.edu.cn