Application of Laser Arc Imaging Technology to Observe Arc Behavior and Contact Motion

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The arc behavior and the contact motion in a miniature circuit breaker with transparent housings are observed by a laser arc imaging system. In the system, an expanded laser beam is used to illuminate the arc quenching chamber, and the chamber with burning arc is recorded by a high speed camera. In front of the camera, an optical band-pass filter is mounted. The recorded frames provide crucial information of the arc behavior and the contact motion. Some quantitative results including displacements and velocity of the movable contacts are collected from the frames.

Keywords: laser imaging technology, arc behavior, contact motion, low voltage circuit breaker

1 INTRODUCTION

Low voltage circuit breakers are widely used in power distribution systems to break the short-circuit current. In the interruption process, the electric arc behavior and the contact motion are important for current limitation.

High speed camera with good temporal-spatial resolution is a direct and effective approach to investigate the arc behavior of circuit breakers. In recent years, the experimental approaches based on high speed camera are rapidly developed. On one hand, combining a high speed camera with a laser source and an optical band-pass filter is a hot topic in this field. On the other hand, much more information can be obtained from the captured frames by the imaging process technique. NakAmura captured the electrode erosion process with a light source illuminating the electrodes [1]. Chen captured the interruption process of a molded case circuit breaker with the same principle [2]. Drebenstedt obtained the exact arc shape and arc root positions with a 405nm optical band-pass filter [3]. In our previous study, the interferometric and schlieren techniques were used to investigate the plasmas and shock waves dynamics during laser triggered discharge in atmosphere [4].

Based on the experiment method of NakAmura and Chen, a laser arc imaging system (LAIS) is built. With this system, the arc behavior and the contact motion of a miniature circuit breaker (MCB) are studied. Some quantitative results including the arc stagnation time on contacts and the movable contact travel are analyzed and compared between 1kA and 3kA experiments. Finally, based on the results of LAIS, some causes of back restrike are discussed.

2 EXPERIMENT SETUP

The experiment system includes a capacitor bank circuit, a LAIS, and a control and measurement system, shown in Fig.1. The capacitor bank circuit provides short-circuit currents of 1kA and 3kA at 50Hz. The LAIS is composed of a green laser source, a beam expander, and a high speed camera with an optical narrow band-pass filter. The LAIS is on the side of the testing circuit breaker with a transparent housing. The expanded laser beam passes through the transparent housing, and illuminates the arc chamber. The chamber with the burning arc is recorded by the high speed camera installed perpendicularly to the circuit breaker. The wavelength of laser is 532nm, and the central wavelength of the filter is also 532nm with full width at half maximum of 3nm. Therefore, the diffuse reflected laser is able to pass through the filter, while only a few portion of arc light at a wavelength near 532nm can pass through. The incidence angle of the laser is of crucial importance. With a small incidence angle, the camera captures much laser reflected from the surface of transparent housing. While with a large incidence angle, the camera captures a little laser reflected from the quenching chamber. Based on the experiment experience, an incidence angle in the range of 15 to 30 degrees is proper. The control and measurement system consists of a digital trigger, a thyristor, an oscilloscope, a high-voltage probe and a Rogowski coil. The digital trigger outputs synchronizing pulse signals to trigger the thyristor, the oscilloscope and the high speed camera. The oscilloscope records the arc voltage and the short-circuit current through the high-voltage probe and the Rogowski coil, respectively.

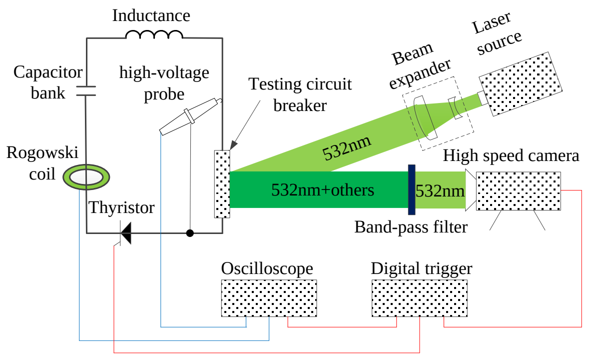


Fig.1: Schematic diagram of experiment system

The quenching chamber of the circuit breaker consists of a movable contact, a static contact, two arc runners, and arc chutes, shown in Fig.2. The contacts are in close position, and can be opened by an operating mechanism. In order to observe the arc in arc chutes, the arc chutes are fixed by narrow battens.

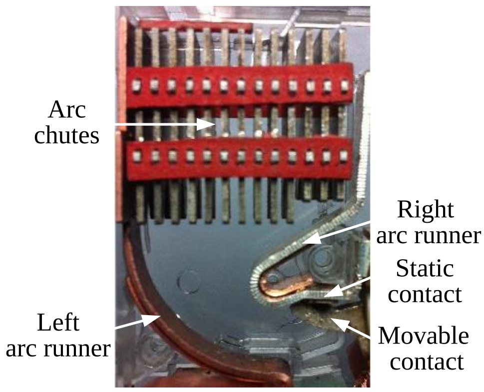


Fig.2: Structure of arc quenching chamber

3 RESULTS AND DISCUSSION

3.1 1kA INTERRUPTION EXPERIMENT RESULTS

Fig.3 shows the arc voltage and the short-circuit current waveforms in a 1kA interruption experiment. At 0ms, the short-circuit current starts to increase, while the arc voltage is still zero. At 3.334ms, the movable contact starts to move, and the arc voltage steps up to 20V, which equals to the minimum arcing voltage of the contact material. The arc current reaches the peak value of 1.4kA at 3.8ms, and then decreases to zero at 8.5ms. However, the arc voltage oscillates around 150V for back restrikes after 4ms, and decreases to -166V, which is the residue voltage of the capacitor bank.

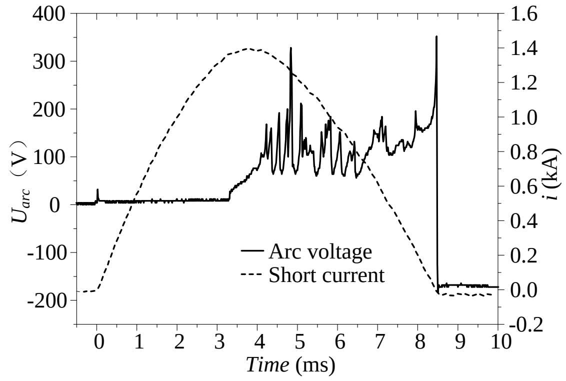
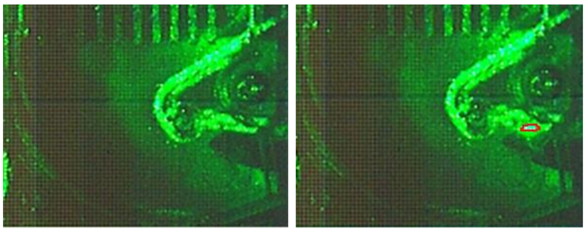


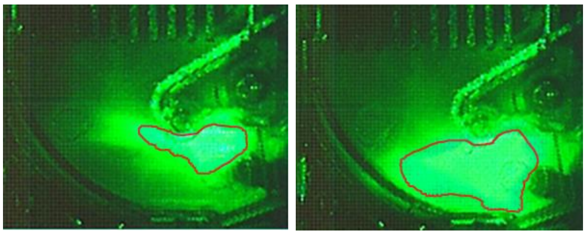
Fig.3: Arc voltage and short-circuit current

This paper is mainly focused on the early arc phenomenon including arc generation, arc motion and back restrike. The arc quenching period is not included in this paper. Twelve key frames marked a, b, ⋯, l, are shown in Fig.4, and the arc region is highlighted by red circles. It is found that the arc and the arc quenching chamber, especially the movable contact, are well captured by the LAIS. The components of the chamber in silver, such as arc chutes and the right arc runner, reflect the green laser intensely, and are captured in green. However, the components in brown, such as the movable contact and the left arc runner, absorb the green laser strongly, and are captured in black. As for the arc, there are several spectral lines around 532nm. Therefore, the arc is captured in bright green, and it is in white if overexposure.

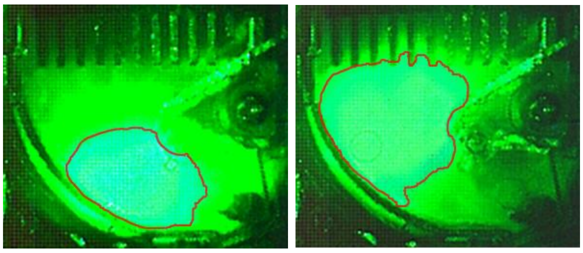
Based on the frames, the movable contact travel is obtained. Firstly, the real value of arc chute length is measured. Secondly, the number of pixels in range of arc chute length is measured in the frames, so the number of pixels per millimeter is yielded. Thirdly, the bottom of movable contact is set as a beacon, and the displacement of the beacon in pixel is measured one frame by one frame. Finally, based on the number of pixels per millimeter, the displacement of the beacon is converted to values in millimeter, and the movable contact travel is shown in Fig.5. It is found that the travel from 4.5ms to 5.2ms is not shown. That is because the beacon moves out of the camera view. In Fig.5, the arc voltage is shown again with the markers a, b, ⋯, l, which are related to the markers in Fig.4. Combining Fig.4 and Fig.5, the arc behavior and contact motion are analyzed in the following.



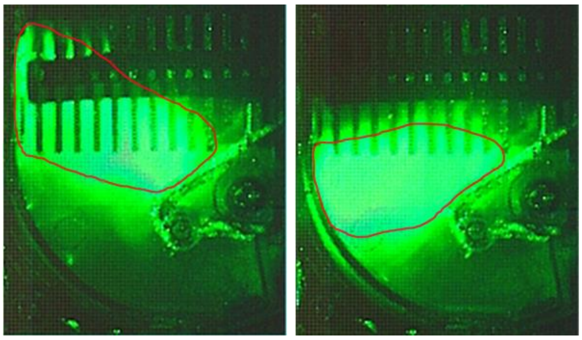
(a) 3.286ms, U_{arc}=0V *(b) 3.334ms, U_{arc}=20V*



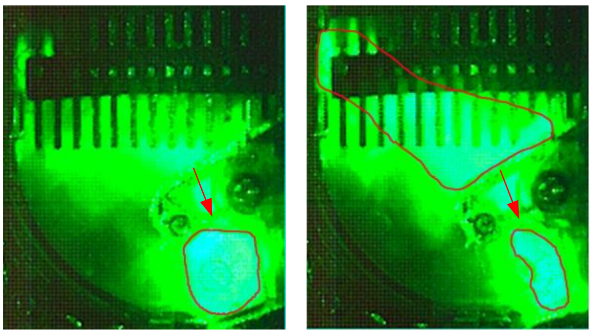
(c) 3.619ms, U_{arc}=35.6V *(d) 3.761ms, U_{arc}=47.6V*



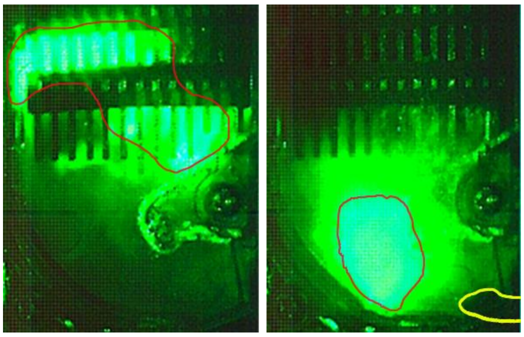
(e) 3.904ms, U_{arc}=60V *(f) 4.0ms, U_{arc}=60V*



(g) 4.22ms, U_{arc}=148V *(h) 4.24ms, U_{arc}=100V*



(i) 4.36ms, U_{arc}=68V *(j) 4.56ms, U_{arc}=100V*



(k) 4.83ms, U_{arc}=308V *(l) 5.83ms, U_{arc}=58V*

Fig.4: Frames of arc and contact motion

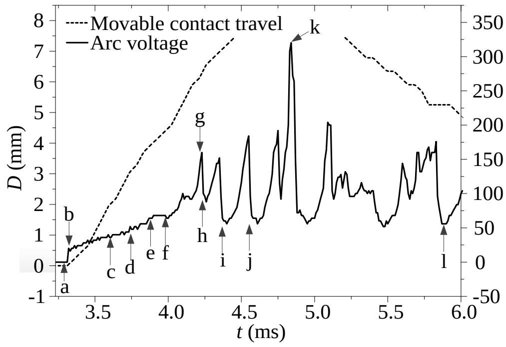


Fig.5: Arc voltage and movable contact travel

(1) Arc generation

The contacts are still closed at 3.286ms in Fig.4 (a), and start to open at 3.334ms in Fig.4 (b). Meanwhile, the arc is generated between contacts, and the arc voltage steps up to 20V. After that, the arc voltage increases with the motion of the movable contact, shown in Fig.5.

(2) Arc root transferring to arc runner

Due to the arc-blowing force and the expansion pressure, the arc starts to spray hot gas to the gap between arc runners, shown in Fig.4 (c). The hot gas accelerates the strike of the arc runner gap, and is good for the arc root transfer. Fig.4 (d) shows the frame that the arc roots are moving from contacts to arc runners.

(3) Arc motion to arc chutes

From Fig.4 (e) to Fig.4 (f), the arc rotates around the right arc runner to move to the arc chutes, and the voltage stays at 60V, shown in Fig.5. This is because the arc length is almost the same at this stage. After that, the arc voltage goes up with the increasing arc length. Fig.4 (g) shows that the left part of the arc moves into the arc chutes, while the right one still stays out of the arc chutes. Meanwhile, the arc voltage increases to 148V rapidly, which results from the electrode voltage drop of the arc chutes, when the arc is cut into several short arcs by the arc chutes.

(4) Back restrike

Just after the left part of the arc moving into the arc chute, a back restrike occurs at the inlet of the arc chutes, shown in Fig.4 (h). Meanwhile, the arc voltage decreases to 100V rapidly, and then the arc voltage increases again with the arc motion into the arc chutes, shown in Fig.5. After that, there are two times of back restrikes which occur at the contact area at 4.36ms and 4.56ms, as shown in Fig.4 (i, j). At that time, the arc voltage falls to 60V rapidly, however, then increases slowly again with the arc motion from the contact area towards the arc chutes. Therefore, the back restrike causes the downwards pulse in the arc voltage curve, and the downwards pulse is the wider and deeper, when the position of the back restrike is closer to the contact area. In Fig.4 (k), the arc almost moves into the arc chutes, and the left part moves further. Meanwhile, the arc voltage reaches the peak value of 308V. In Fig.4 (l), the rebound contact is clearly seen, and is highlighted with a yellow line. The movable contact travel is decreased to 5mm, shown in Fig.5, i.e. 60% of the maximum.

3.2 COMPARISON OF QUANTITATIVE RESULTS

The arc evolution process of the 3kA experiment is similar to that of 1kA, but the quantitative results are different, listed in Tab. 1. Compared with the results of the 1kA experiment, i_t is 50% larger in the 3kA experiment for the higher current rise rate, and t_1 decreases by 66.7%, because of the larger Lorenz force on the arc. v increases by 18% due to the larger Lorenz force on the movable contact and the larger acting force from the release. As for U, it also increases by 7.4%.

Tab.1: Comparison of quantitative results

I(kA)	i_t(kA)	t_1(ms)	v (mm/ms)	U(V)
1kA	1.36	0.57	6.83	110.8
3kA	2.05	0.38	8.11	119

I: Effective value of prospective short-circuit current

i_t: Transient current when contacts separating

t_1: Arc stagnation time on contacts

v: Average repulsion velocity of the contact

U: Average arc voltage

3.3 DISCUSSION

It is known that the occurrence of the back restrikes may have negative effects on the current-limiting performance and interruption capability. From the above experimental results, it is found that several factors may induce the back restrikes. Firstly, after the arc moving into the arc chutes, the arc voltage is increased rapidly. It is good for limiting current, but increases the gap voltage of contacts and arc runners. Secondly, the residual hot gas and the diffused hot gas reduce the critical electric strength between contacts or arc runners. In Fig. 4 (g), the residual hot gas at the inlet of arc chutes may induce the back restrike of Fig. 4 (h). In Fig.4 (i, j), a portion of hot gas marked a red arrow line, diffuses from the arc chutes to the contact area, which may be a reason of the back restrikes. In addition, the contact rebound reduces the breakdown voltage of the contact gap too.

4 CONCLUSION

(1) The laser arc imaging system is able to capture the arc and the quenching chamber simultaneously, and the frames of arc behaviour and contact motion are clear.

(2) Based on LAIS, it is clear seen that the movable contact rebounds 40% of the maximum contact travel in the 1kA experiment.

(3) The average repulsion velocity of movable contact is increased by 18% with the short-circuit current increasing from 1kA to 3kA.

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