Distribution of Breakdown Positions in Conditioning Progress Between Plane-Plane Electrodes in Vacuum Under Lightning Impulse Voltage

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Abstract. The purpose of this paper is to determine the distribution of the breakdown locations between plane-plane electrodes in the conditioning progress of the vacuum interrupter. The material of the experimental plane-plane electrodes was CuCr50. The gap length between electrodes was set at 1.0 mm. A standard negative lightning impulse voltage was applied. The breakdown location was decided by the breakdown photo at different perspectives by a high-speed camera, with recording speed of 5.8×10^5 frames/s. The experimental results indicate that the conditioning area covered the entire surface of the contact during the conditioning process. The distribution of breakdown locations was random distribution during the conditioning progress. In the initial conditioning progress of a small vacuum gap, the breakdown locations weren't only distributed in the region where the electric field was highest. The strength of the electric field might not be the primary key factor that determined the breakdown position distribution during the conditioning process.

Keywords: Vacuum interrupter · Breakdown position · Conditioning progress · Plane-Plane electrode · Lightning impulse voltage

1 Introduction

There has been an increasing interest to develop the vacuum circuit breaker due to their advantages. The vacuum applications are expected to be extended to the higher voltage, in order to replace SF_6 circuit breakers due to its greenhouse effect. However, the internal insulation problems of the vacuum circuit breakers restrict this development [1]. Thus, the electrodes are conditioned to strengthen the electric field intensity. As is known to all, spark conditioning through the repeated breakdown is one of the effective means to enhance the dielectric strength ability of one vacuum gap [2].

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Many researches on the conditioning characteristics and its influencing factors have been completed on the basis of theoretic and experimental analysis. Okubo *et al.* [3] assumed the relationship between the field emission and the breakdown illumination spot and put forward the model reflecting the conditioning mechanism. Y. Inagawa *et al.* [4] investigated the transfer of the illumination spot of the rod-plane electrodes with different surface roughness. F. Miyazaki *et al.* [5] revealed the transition of the breakdown spot region on the rod electrode and the corresponding breakdown field strength in the conditioning process. Y. Fukuoka *et al.* [6] observed the transition of the breakdown spot under the vacuum gap distance of 5 mm and 30 mm, respectively. X. Ma *et al.* [7] studied the distribution of the breakdown locations in vacuum between the sphere-plane electrodes under the different breakdown energy.

However, the previous researches did not reveal the distribution characteristics of the breakdown locations in conditioning progress of the contact in the vacuum interrupter clearly yet. Thus, the purpose of this paper is to investigate the specific distribution characteristics of the breakdown locations between the plane-plane electrodes in conditioning progress in vacuum under the lightning impulse voltage. The experimental results are beneficial to recognize the conditioning progress inside the vacuum interrupter.

2 Experimental Setup

Figure 1 shows the electrode configuration in the vacuum interrupter. The test specimen was a vacuum interrupter made up of the plane-plane electrodes and a glass tube, which can make the recording of the breakdown easily. The electrode material was made of CuCr50 (50%Cr). The diameter of the electrodes was 18 mm. The chamfering radius of the electrode edge was 1 mm. The diameter of the conductive rod was 12 mm. The thickness of the electrode was 5 mm. In the experiment, the electrode gap was fixed at 1.0 mm.

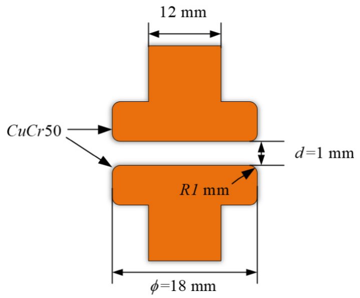


Fig. 1. Electrode configuration

Figure 2 displays the schematic of the experimental circuit system. A negative standard lightning impulse voltage (−1.2/50 µs) generated by a lightning impulse generator (300 kV/15 kJ) was applied to the electrode gap. The static electrode was grounded. The impulse voltage and breakdown current were measured by a voltage divider and a

Pearson current transformer, respectively, and were recorded by a digital oscilloscope. The limiting resistance R_L was 100 Ω. A high-speed camera was used to observe the conditioning process of the vacuum gap. The recording speed of the high-speed camera was 5.8×10^5 frames/s. For voltage application, the up-and-down method was used. The experiment was started from 20 kV with a voltage step of 2 kV.

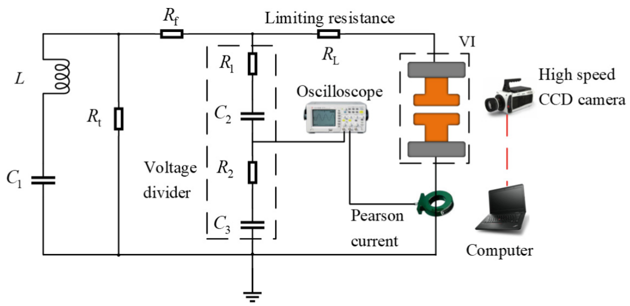


Fig. 2. Experimental circuit system

Figure 3 displays the design scheme of the light path that can achieve shooting at two angles of the electrodes by using only one camera. Based on the reflection principle of light, the light emitted from the center of the plane electrode is reflected by the plane mirrors and enters the high-speed camera. The function of this light path design scheme is to achieve two right-angled cameras (camera 1 and camera 2) shooting the breakdown in the vacuum gap. As labeled in Fig. 3, $\alpha 1 = \alpha 2 = 45^{\circ}$, $\alpha 3 = \alpha 4 = 45^{\circ}$, $\beta 1 = \beta 2 = 22.5^{\circ}$, $\beta 3 = \beta 4 = 22.5^{\circ}$.

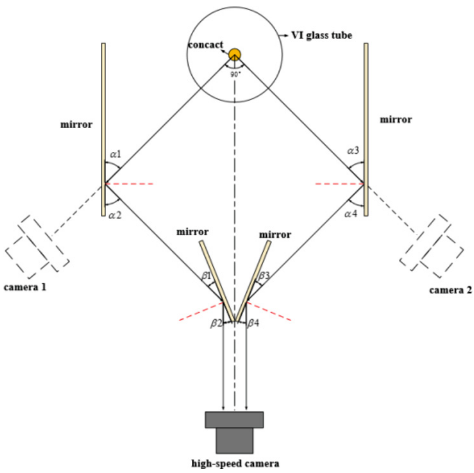


Fig. 3. Light path design scheme ($\alpha 1 = \alpha 2 = 45^{\circ}$, $\alpha 3 = \alpha 4 = 45^{\circ}$, $\beta 1 = \beta 2 = 22.5^{\circ}$, $\beta 3 = \beta 4 = 22.5^{\circ}$)

Figure 4 displays the image of illumination spot of the breakdown positions. The red dashed line represents the center line of the contact. *d1* and *d2* represent the distance between the center of the illumination spot and the center of the contact, respectively. Figure 5 shows the method for determining the breakdown position. The red dashed line in Fig. 5 represents the right-angled coordinate reference line through the center of the circle. The position of *d1* and *d2* in Fig. 4 can be determined in Fig. 5. The intersection of the two straight lines passing through *d1* and *d2* is the center position of the illumination spot.

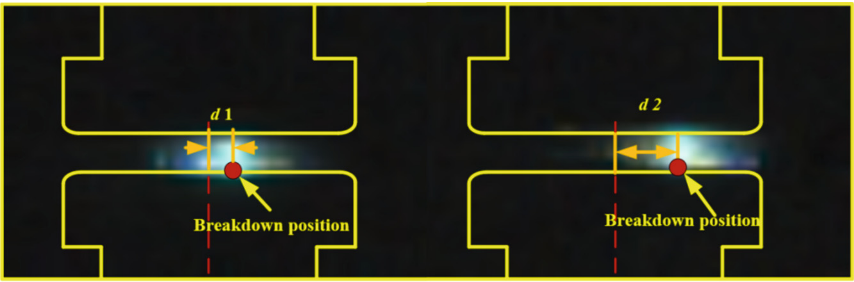


Fig. 4. Image of illumination spots of breakdown positions

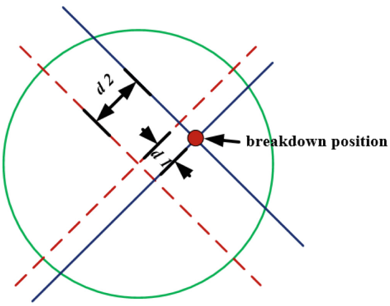


Fig. 5. Method for determining breakdown positions

3 Experimental Results

Figure 6 shows the conditioning history from 20 kV to 68 kV of CuCr50 electrodes under the gap distance of 1.0 mm. The electrodes were conditioned 2020 times. As shown in Fig. 7, the contact surface was divided into five regions starting from the center to the edge. These regions were labeled from No. 1 to No. 5 with different color. Region 1 was a circle with a diameter of 2 mm. The radius values of adjacent circles differed by 2.0 mm.

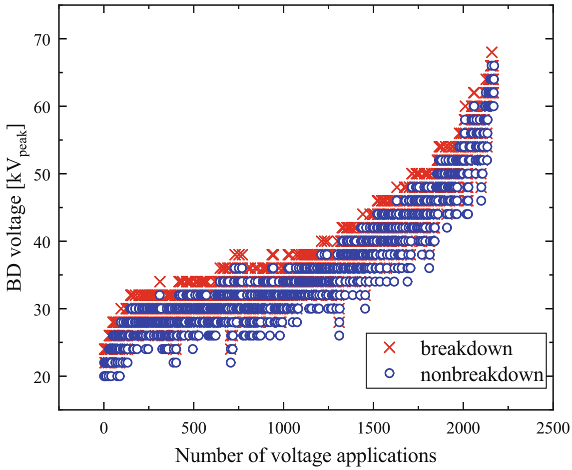


Fig. 6. Conditioning history of CuCr50 electrodes by up-and-down method ($d = 1$ mm)

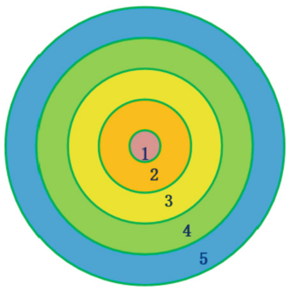
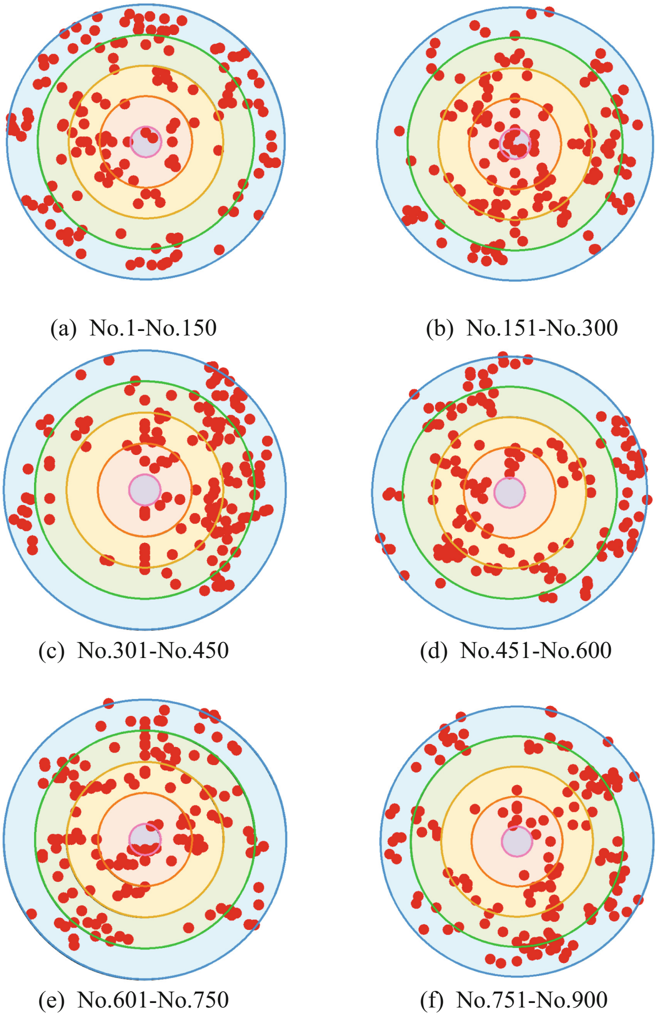


Fig. 7. Schematic diagram of regional division

Figure 8 shows the breakdown positions in each region for every 150 breakdowns in the conditioning duration. As shown in Fig. 8(a), in the initial 150 times breakdowns, the breakdown positions distribute to any point in the contact surface. From Fig. 8(b) to Fig. 8(f), there was no a special region where the breakdown positions got together. Figure 9 shows the distribution of breakdown positions during total 900 breakdowns. It shows that the conditioning area covered all the electrode surface.

As shown in Fig. 10, for the No. 1–No. 150 breakdown, the ratios of the breakdown locations in the divided regions from No. 1 to No. 5 were 1.3%, 10.7%, 18%, 20%, 50%, respectively. For the next No. 151–No. 300 breakdown, the ratios of the breakdown locations in the divided regions from No. 1 to No. 5 were 4.7%, 13.3%, 28%, 24.7%, 29.3%, respectively. Based on the total 900 breakdowns, the results implies that the distribution of breakdown positions was random distribution during the conditioning process.



(a) No.1-No.150
(b) No.151-No.300
(c) No.301-No.450
(d) No.451-No.600
(e) No.601-No.750
(f) No.751-No.900

Fig. 8. Transition of the breakdown discharge spot region during the conditioning process

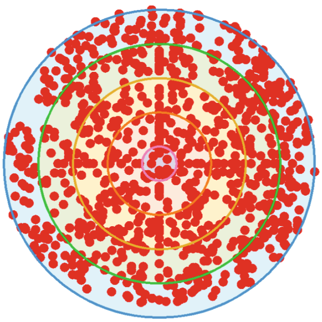


Fig. 9. Distribution of breakdown positions (900 breakdowns)

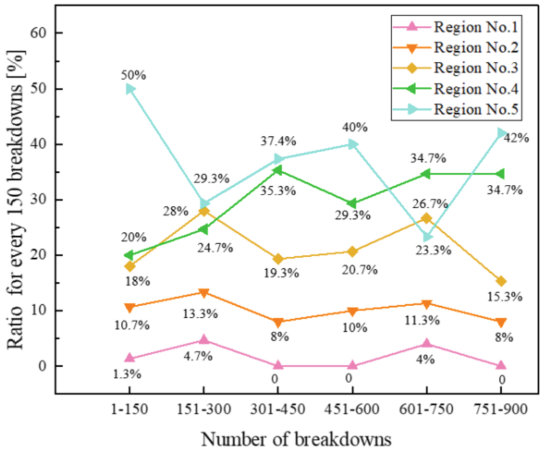


Fig. 10. Ratio of breakdown positions in five regions during the conditioning process

4 Simulation

Figure 11 displays the results of the electric field strength distribution between electrodes. The electrode gap was 1 mm. High voltage 1 kV was applied to the moving electrode, and 0 kV was applied to the static electrode. Figure 12 shows the value of electric field strength distribution along the contact surface under the gap of 1.0 mm. The electric field strength value in region from No. 1 to No.4 was all at 1.0 kV/mm. The electric field strength value in region No. 5 ranged from 0.33 kV/mm to 1.12 kV/mm.

Average field strength E_{av} was calculated, according to the following formula.

$$E_{av} = \frac{U}{d} \tag{1}$$

where, U is the applied voltage and d is the gap length.

The breakdown field strength E_{B} was given by

$$E_B = \beta_m \beta_g E_{av} \tag{2}$$

where, β_m is the microscopic field intensification factor and β_g is the macroscopic field intensification factor.

In the simulation, β_g was calculated, according to the following formula.

$$\beta_g = \frac{E}{E_{av}} \tag{3}$$

where, E_{av} was 1 kV/mm, according to the formula (1).

According to the formula, β_g and E were equal in value. The simulation result implies that the electric field intensity and the β_g on the edge of the electrode are stronger than that on any other regions of the electrode. The simulation results under each voltage value have the same law as mentioned.

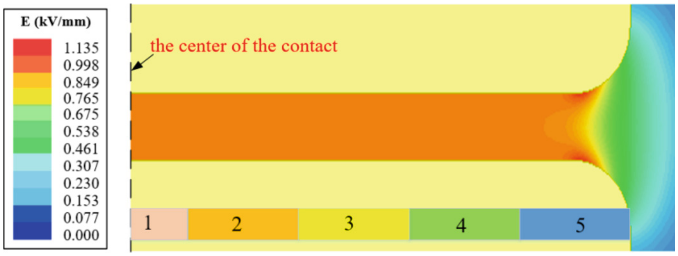


Fig. 11. Electric field distribution between electrodes

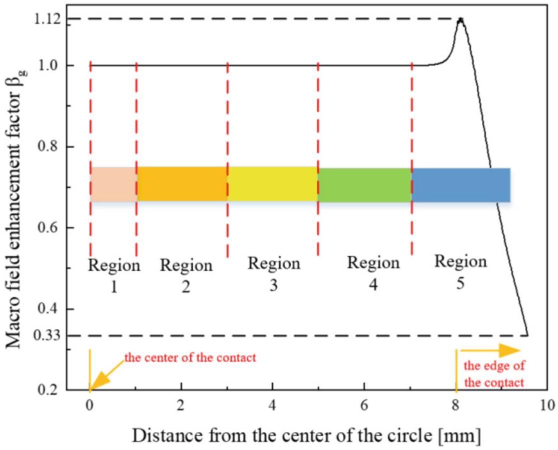


Fig. 12. Electric field strength value along the surface of the contact

5 Discussion

As shown in Fig. 12, β_g of the experimental electrodes ranged from 0.33 to 1.12 according to the simulation. For the vacuum interrupter model with copper material, β_m was around 500 [8]. Likely, for plane-plane electrode, β_m was much larger than β_g. The influence of β_m on the electric field strength might be more significant than that of β_g. β_m on the surface of the electrode shows different values depending on the machining process of electrodes. Breakdown weakness of the higher β_m might be randomly distributed on the electrode surface. Thus, breakdowns occurring in the region of the contact was random, as shown in Fig. 9. It could be concluded that the geometry field strength might not be the primary key factor that determined the breakdown position distribution during the initial conditioning process.

6 Conclusion

In this paper, the distribution of the breakdown locations between plane-plane electrodes in vacuum under the lightning impulse voltage has been determined experimentally. The following conclusions can be drawn.

1) The conditioning area covered the entire surface of the contact during the conditioning process. The distribution of breakdown positions was random distribution during the conditioning progress.
2) In the initial conditioning progress of a small vacuum gap, the breakdown positions weren't only distributed in the region where the electric field was highest. The strength of the electric field might not be the primary key factor that determined the breakdown position distribution during the conditioning process.

References

1. Okubo, H., Kojima, H., Kato, K.: Advanced electrical insulation techniques for higher voltage vacuum interrupters. CIGRE B3/D1 Colloquium, no. 218 (2013)
2. Slade, P.G.: The Vacuum Interrupter: Theory, Design, and Application, chap. 1. CRC Press, Boca Raton (2008)
3. Okubo, H., Miyazaki, F., Inagawa, Y., et al.: Electrode area of breakdown depending on conditioning mechanism under non-uniform electric field in vacuum. In: 2004 Proceedings of the XXIst International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), Yalta, Ukraine, pp. 76–79 (2004)
4. Inagawa, Y., Miyazaki, F., Kato, K., et al.: Effect of electrode surface roughness on breakdown conditioning process under non-uniform electric field in vacuum. In: 2004 Proceedings of the XXIst International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), Yalta, Ukraine, pp. 72–75 (2004)
5. Miyazaki, F., Inagawa, Y., Kato, K., et al.: Electrode conditioning characteristics in vacuum under impulse voltage application in nonuniform electric field. IEEE Trans. Dielectr. Electr. Insul. **12**(1), 17–23 (2005)
6. Fukuoka, Y., Yasuoka, T., Kato, K., et al.: Breakdown conditioning characteristics of long gap electrodes in a vacuum. IEEE Trans. Dielectr. Electr. Insul. **14**(3), 577–582 (2007)
7. Ma, X., et al.: Effect of limiting resistance on distribution of breakdown positions under lightning impulse voltage between sphere-plane electrodes in vacuum. In: 2020 IEEE International Conference on High Voltage Engineering and Application (ICHVE), Beijing, China, pp. 1–4 (2020)
8. Okawa, M., Shioiri, T., Okubo, H., et al.: Area effect on electric breakdown of copper and stainless steel electrodes in vacuum. IEEE Trans. Electr. Insul. **23**(1), 77–81 (1988)