Lighting Impulse Voltage Breakdown Characteristics of Vacuum Interrupters with 10 to 50mm Contact Gaps

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***ABSTRACT*- The objective of this paper is to understand the standard lighting impulse voltage breakdown characteristics of vacuum interrupters with contact gaps 10 to 50mm and how contact parameters influence the breakdown characteristics. The investigated contact parameters include contact diameter 75mm and 60mm, contact surface roughness 1.6 μ m and 3.2 μ m, and contact radius of curvature 6mm and 2mm. Therefore we designed four high-voltage vacuum interrupters in the experiments. The vacuum interrupters were put into a porcelain envelope with SF_6 gas as an external insulation of the vacuum interrupters. The contact gaps can be adjusted manually. Negative polarity basic impulse level (BIL) voltage (1.2×50μs) was applied by an up-and-down method. Experimental results revealed the breakdown probability distribution followed a Weibull distribution when the breakdown voltage saturated in the investigated contact gaps 10 to 50mm. And 50% breakdown voltage U_{50} depends on the contact gap d (10~50mm), can be expressed by an equation $U_{50}=kd^{\alpha}$, where α is a power exponent; k denotes a coefficient which is determined by experiments. Within the contact gaps 10 to 50mm, U_{50} of vacuum interrupter with contact radius of curvature 2mm was significantly higher than that of vacuum interrupter with contact radius of curvature 6mm. And U_{50} of contact roughness 1.6μm was close to that of contact roughness 3.2μm. U_{50} of the contact diameter 60mm was close to that of contact diameter 75mm.**

I. INTRODUCTION

Vacuum Circuit Breakers (VCBs) are widely used for medium voltage due to their excellent features such as ease of maintenance and less environmental impact etc. At present, they are required to be applied to the higher voltage systems. This makes it important to ensure the reliability of the insulation of high-voltage vacuum interrupters (VIs). So the insulation characteristics of VIs must be investigated [1,2].

There are a lot of work has been done on vacuum insulation. Shioiri et al. [1] investigated the effects of test methods, electrode area, and electrode materials on the breakdown probability distributions of uniform field gaps with contact gap 3mm. Kato and Okubo et al.[2] discussed the conditioning characteristics used rod-to-plane electrodes with changing the gap distance d=2~50mm, under non-uniform electric field in vacuum. Sato et al.[3] discussed the relationship between breakdown voltage of vacuum gaps and electrode surface roughness for plate-to-plate electrodes. Several authors [4-6] studied the area effect on electric breakdown. However, the breakdown voltage characteristics in high voltage vacuum interrupters with contact gaps of several tens of mm are unclear.

The objective of this paper is to understand the standard lighting impulse voltage breakdown characteristics of vacuum interrupters with contact gaps 10 to 50mm and how contact parameters influence the breakdown characteristics. The investigated contact parameters include contact diameter 75mm and 60mm, contact surface roughness 1.6 μ m and 3.2 μ m, and contact radius of curvature 6mm and 2mm. The results could provide some useful information for high voltage vacuum interrupters insulation design.

II. EXPERIMENTAL SETUP

In this paper, we specially designed four VIs to understand the standard lighting impulse voltage breakdown characteristics of vacuum interrupters with contact gaps 10 to 50mm and compare the influence of three different contact parameters on the breakdown characteristics of VIs with contact gaps 10~50mm. The three contact parameters are contact radius of curvature 2mm and 6mm, contact surface roughness 1.6 μ m and 3.2 μ m, and contact diameter 60mm and 75mm as shown in Table.1. The electrodes of the four VIs were shown in Fig.1. The contact material of the four VIs was CuCr40. The thickness of the electrodes was 15mm. The contact gap was 10~50mm.

The breakdown voltage characteristics were measured in vacuum interrupters at a pressure of 10^{-5}Pa. The vacuum interrupters were put into a porcelain envelope with SF_6 gas as an external insulation. And the SF_6 pressure in the porcelain envelope was 0.25MPa. The contact gap was adjusted up to 50mm through a gap spacing adjuster. Dielectric tests were carried out by up-and-down method [7] and ΔV was set as ~4kV. The occurrence of a breakdown was determined by observing the voltage waveforms on a digital oscilloscope.

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TABLE 1.
CONTACT EDGES, CONTACT DIAMETERS AND SURFACE ROUGHNESS OF THE PLATE-TO-PLATE CONTACT*

VIs	Contact radius of curvature (mm)	Surface Roughness (μm)	Contact Diameter (mm)
No.1	6	1.6	60
No.2	2	1.6	60
No.3	6	3.2	60
No.4	6	1.6	75

* No.1 VI is a benchmark for comparison with other interrupters in one contact design parameter.

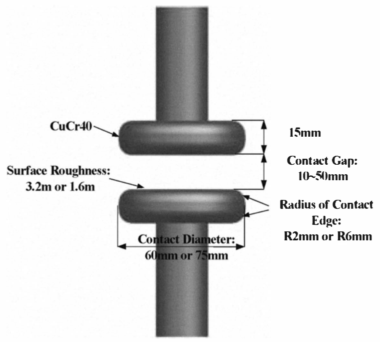

Fig.1 Configuration of plate-to-plate electrodes

III. EXPERIMENTAL RESULTS

In the conditioning process, the breakdown voltage at the n^{th} voltage application U_{BN} is increasing as the voltage application N increasing. But the U_{BN} tends to a limited value U_L ($N \to \infty$). When the ratio of U_{BN}/U_L is 0.95 and above, the conditioning process is considered entering saturation, which is the criterion of "saturation" in our experiments [6].

Fig.2 shows the conditioning history of the breakdown voltage by the up-and-down method for four interrupters with different contact parameters with contact gaps 10mm to 50mm. As shown in Fig.2, the breakdown voltage saturated for four interrupters with different contact gaps on different number of voltage application. The arrows in Fig.2 indicate the points of voltage application after which breakdown voltage entering saturation. When the breakdown voltage saturated, the breakdown probability distribution on different contact gaps followed a Weibull distribution. So the 50% breakdown voltage U_{50} can be obtained from the Weibull distribution. Table 2 shows the gap length, number of voltage application till the U_{BN} saturated, 50% breakdown voltage U_{50} [kV], i.e. according to Fig.2.

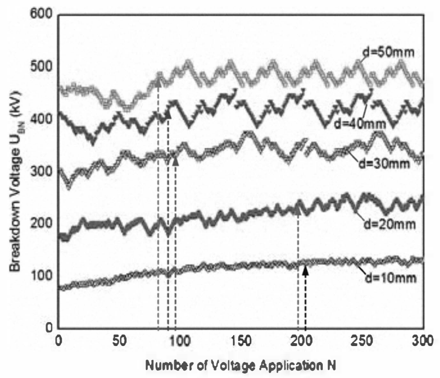

Fig.2a Conditioning history of No.1 VI as a benchmark. The arrows indicate the breakdown voltage entering saturation

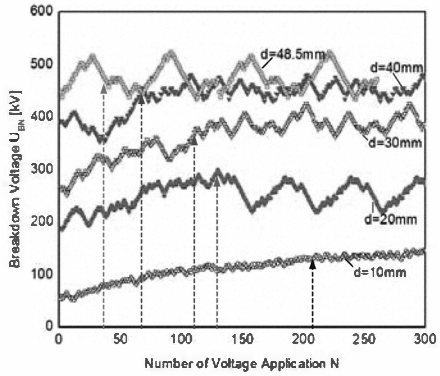

Fig.2b Conditioning history of No.2 VI (No.2 VI with the contact radius of curvature is 2mm and different with No.1). The arrows indicate the breakdown voltage entering saturation

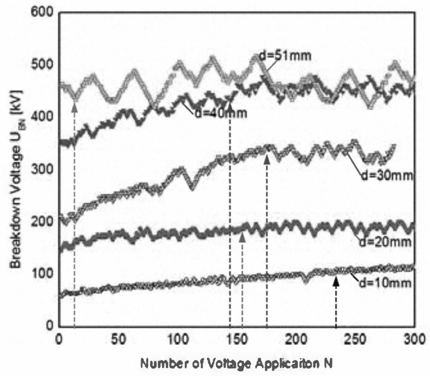

Fig.2c Conditioning history for No.3 VI (No.3 VI with the surface roughness is 3.2 μ m and different with No.1). The arrows indicate the breakdown voltage entering saturation

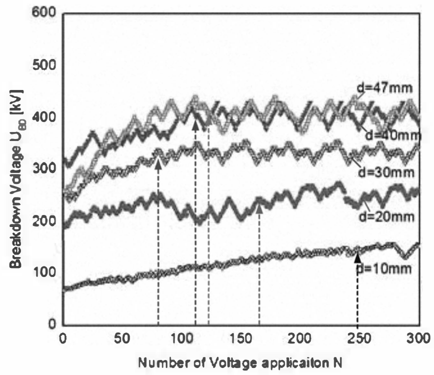

Fig.2d Conditioning history for No.4 VI (No.4 VI with the contact diameter is 75mm and different with No.1). The arrows indicate the breakdown voltage entering saturation

TABLE 2. THE GAP LENGTH, NUMBER OF VOLTAGE APPLICATION TILL THE U_{BN} SATURATED, 50% BREAKDOWN VOLTAGE U_{50} [kV]

	Gap Length (mm)	Number of Voltage application till U_{BN} is saturated	50% Breakdown Voltage U_{50} [kV]
No.1 electrodes	10	210	149
	20	197	239
	30	97	331
	40	90	402
	50	82	457
No.2 electrodes	10	211	164
	20	126	276
	30	114	380
	40	70	451
	48.5	41	473
No.3 electrodes	10	237	154
	20	156	181
	30	175	331
	40	148	400
	51	17	469
No.4 electrodes	10	250	176
	20	164	230
	30	79	333
	40	105	394
	47	124	412

III. DISCUSSIONS

A. *Characteristics of 50% Breakdown Voltage U_{50}*

Fig.3 shows the relationship between U_{50} and the gap length for the four interrupters. From Fig.3a, for No.1 VI as a benchmark, the relationship between U_{50} and gap length d was approximated by

$U_{50}=27\times d^{0.74}$ (10mm<=d<=30mm) (1)

$U_{50}=39\times d^{0.63}$ (30mm<=d<=50mm) (2)

From Fig.3b, for No.2 VI with the contact radius of curvature is 2mm, the relationship between U_{50} and gap length d was approximated by

$U_{50}=28\times d^{0.77}$ (10mm<=d<=30mm) (3)

$U_{50}=82\times d^{0.45}$ (30mm<=d<=48.5mm) (4)

From Fig.3c, for No.3 VI with the surface roughness is 3.2μm, the relationship between U_{50} and gap length d was approximated by

$U_{50}=19\times d^{0.83}$ (10mm<=d<=30mm) (5)

$U_{50}=35\times d^{0.66}$ (30mm<=d<=51mm) (6)

From Fig.3d, for No.4 VI with the contact diameter is 75mm, the relationship between U_{50} and gap length d was approximated by

$U_{50}=50\times d^{0.55}$ (10mm<=d<=30mm) (7)

$U_{50}=66\times d^{0.48}$ (30mm<=d<=47mm) (8)

Fukuoka et al. [2,9] studied the influence of vacuum gap distance between contacts on the breakdown voltage by applying negative standard lighting impulse voltage. They found that the different dependency of gap distance between the short gap range and long gap range (d>=5mm). The power exponent α became smaller when the contact gap got larger. In d=2~5mm, the U_{50} is rising according to the increase in gap distance. On the other hand, the range of 10~50mm, U_{50} is rising slowly to the increase in gap distance. And U_{50} saturated.

Our experimental results under the lighting impulse voltage also supported the findings of Fukuoka et al. [2,9]. We also find the different dependency of contact gaps between different contact gap ranges. In d=5~10mm, α is about 0.8. In d=10~30mm, α is about 0.72. In d=30~50mm, α is about 0.55. As shown in Fig.4, α became lower with the gap became longer. The data of plot with gap length 5~10mm was from reference 10.

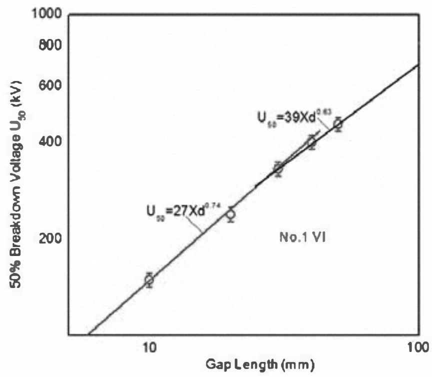

Fig.3a U_{50} as a function of the gap length for No.1 VI (No.1 VI as a benchmark).

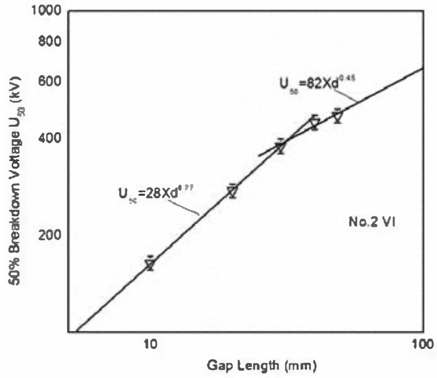

Fig.3b U_{50} as a function of the gap length for No.2 VI (No.2 VI' with the contact radius of curvature is 2mm and different with No.1).

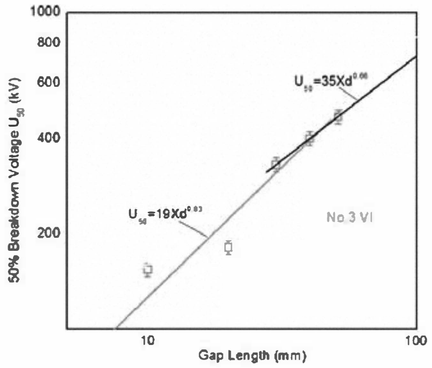

Fig.3c U_{50} as a function of the gap length for No.3 VI (No.3 VI with the surface roughness is 3.2 μ m and different with No.1).

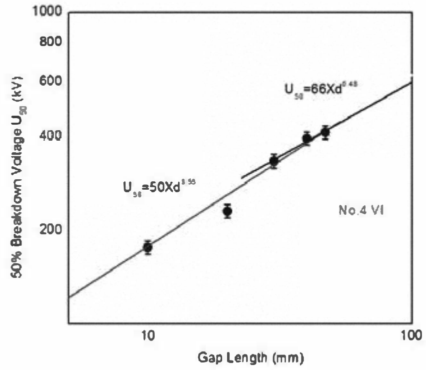

Fig.3d U_{50} as a function of the gap length for No.4 VI (No.4 VI with the contact diameter is 75mm and different with No.1).

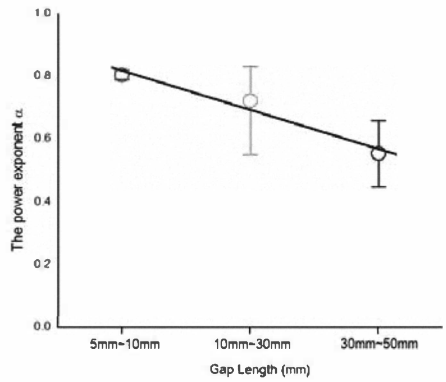

Fig.4 The influence of gap length on the exponent α

B. *The Influence of Contact Parameters on 50% Breakdown Voltage U_{50}*

Within the contact gaps 10~50mm, the influence of contact parameters include contact radius of curvature, contact surface roughness, contact diameter and on breakdown characteristics was shown in Fig.5~Fig.7.

Fig.5 shows the relationship between contact radius of curvature and the 50% breakdown voltage U_{50} of vacuum interrupter. U_{50} of vacuum interrupter with contact radius of curvature 2mm was significantly higher than that of vacuum interrupter with contact radius of curvature 6mm. Fig.6 shows the relationship between contact surface roughness and the 50% breakdown voltage U_{50} of vacuum interrupter. The 50% breakdown voltage of contact roughness 1.6μm was close to that of contact roughness 3.2μm. Fig.7 shows the relationship between contact surface roughness and the 50% breakdown voltage U_{50} of vacuum interrupter. The 50% breakdown voltage of the contact diameter 60mm was close to that of contact diameter 75mm.

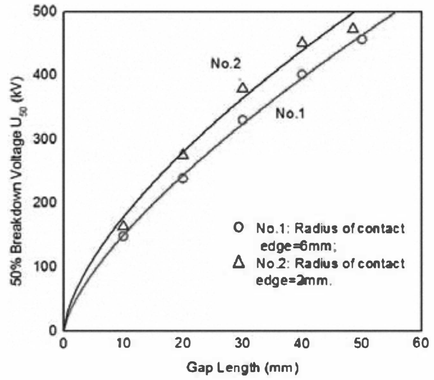

Fig.5 Influence of the contact radius of curvature on breakdown voltage with different gap length

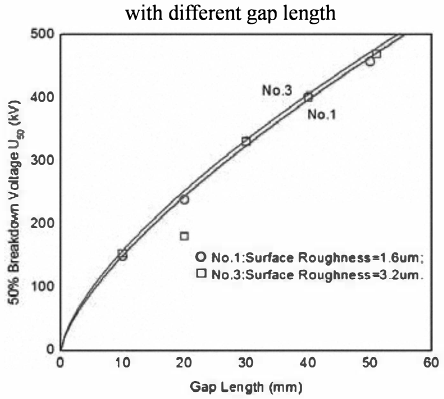

Fig.6 Influence of the contact surface roughness on breakdown voltage with different gap length

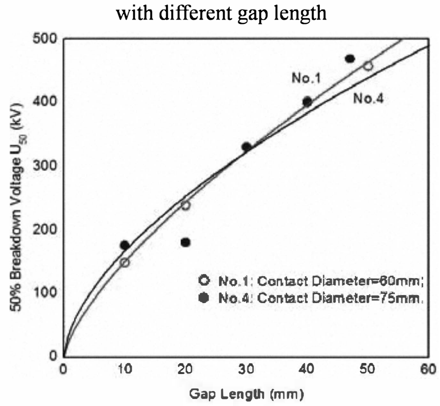

Fig.7 Influence of the contact diameter on breakdown voltage with different gap length

V. CONCLUSIONS

In this paper, we investigated the lighting impulse voltage breakdown characteristics of vacuum interrupters with contact gaps 10 to 50mm and how three contact parameters influence the breakdown characteristics. As a result, the following points were indentified:

(1)The breakdown probability distribution followed a Weibull distribution when the breakdown voltage saturated with contact gaps 10 to 50mm.

(2) 50% breakdown voltage U_{50} depends on the contact gap d, can be expressed by a equation $U_{50}=kd^{\alpha}$. And we found the different dependency of contact gap between d=10~30mm ($\alpha \approx 0.72$) and d=30~50mm ($\alpha \approx 0.55$).

(3)50% breakdown voltage of vacuum interrupter with contact radius of curvature 2mm was significantly higher than that of vacuum interrupter with contact radius of curvature 6mm. And the 50% breakdown voltage of contact roughness 1.6μm was close to that of contact roughness 3.2μm. The 50% breakdown voltage of the contact diameter 60mm was close to that of contact diameter 75mm.

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