Influence of No-load Operation and Current Switching on Breakdown Characteristics of High Voltage Vacuum Interrupters at Contact Gap 30mm

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***ABSTRACT-* It is important to understand dielectric strength of vacuum interrupters after no-load operation and current switching, which reflects a dielectric condition of the vacuum interrupters operating in field. Especially there is no such data available for high voltage vacuum interrupters with contact gaps reaching 30mm. The objective of this paper is to experimentally investigate the influence of three kinds of switching operations on the standard lightning impulse voltage breakdown characteristics of high voltage vacuum interrupters with a contact gap 30mm. The three kinds of switching operations are "closing without current / breaking without current", "closing without current / breaking with 5kA current" and "closing without current / breaking dc current". Therefore we designed six high-voltage vacuum interrupters with butt type contacts. The experimental results revealed that the conditioning process became slowly and the breakdown voltage followed the Weibull distribution after the three kinds of operations. And the operation "closing without current / breaking 5kA current" will increase the 50% breakdown voltage U_{50} of the vacuum interrupter from 340kV to 394kV. The U_{50} of the vacuum interrupter after the operation "closing without current / breaking without current" will increase from 340kV to 362kV. The operation "closing without current / breaking dc current" will increase the dielectric strength. As the current is increasing. The U_{50} increased from 385kV to 395kV with the breaking current 450A dc 500ms. And the U_{50} increased from 385kV to 437kV with the breaking current 750A dc 500ms.**

Ⅰ. INTRODUCTION

Vacuum Circuit Breakers (VCBs) are widely used in medium voltage power distribution system. The advantages of VCBs are as following: ease of maintenance, switched numerous times, compact size, safety and environmental friendly etc. [1, 2]. At present, VCBs have been developed to be used as the high voltage power transmission switching devices. This makes it important to ensure the reliability of the insulation of high-voltage vacuum interrupters (VIs) [3].

VCBs have the excellent abilities of good dielectric strength and arc extinguisher. But it is well known that switching operations have a significant influence on the dielectric strength of VIs. The influence of switching operation on the dielectric of VIs at medium voltage VCBs whose contact gaps are within 20 mm is well studied. He et al. [4] investigated the influence of the short circuit current interruption operations on the dielectric strength for 12kV vacuum interrupters (VIs) with a contact gap 10mm. They found that the dielectric strength of the VIs decreased significantly after the short circuit current interruption. The proposed reasons were that the high current vacuum arc destroyed the contact surface by ejecting many metal particles and metal vapor. Sandolache and Rowe [5] found that the micro-particles produced by current interrupting operations would decrease the dielectric strength of VIs. And the switching operation "closing without current / breaking without current" also has a significant influence on the dielectric strength of VIs. Osmokrović [6] studied the influence of switching operations "closing without current/ breaking without current", "closing without current / breaking with rated current", and "closing without current / breaking of rated of short - circuit current" on ac breakdown voltage of vacuum interrupters. He found that the conditioning process of ac voltage strongly depended on the type of the switching operation performed before dielectric testing. It has been established that the switching operation "closing without current/ breaking without current", as well as the switching operation "closing without current / breaking of rated of short - circuit current", significantly reduces the ac breakdown voltage of the vacuum interrupters. And the switching operation "closing without current / breaking with rated current" does not cause a change in the ac voltage conditioning process. But the withstanding ability after condition process increased after the switching operations except the operation "closing without current / breaking of rated of short - circuit current". Zalucki et al [7] studied the influence of switching operations, "closing with current / breaking with current" and "closing without current/ breaking without current", on the dielectric strength in vacuum interrupters. They found that the reason for a decreasing of the dielectric strength was melting of contact surface during the switching process.

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However, there is no data available for high voltage vacuum interrupters with contact gaps reaching 30mm, which is a contact gap in a 72.5kV vacuum interrupter. The objective of this paper is to experimentally investigate the influence of three kings of switching operations on standard lightning impulse voltage breakdown characteristics of high voltage vacuum interrupters with a contact gap 30mm. We designed six VIs with butt type contacts. First, we investigated the lightning impulse breakdown voltage of VIs with two kinds of breaking current in switching operation “closing without current / breaking dc current”. Then we investigated the lightning impulse breakdown voltage of VIs with switching operations “closing without current / breaking without current” and “closing without current / breaking with 5kA current” on breakdown voltage.

II. EXPERIMENTAL SETUP

We used six VIs to understand the influence of the three kinds of switching operations on the standard lightning impulse voltage breakdown characteristics of the vacuum interrupters with contact gap 30mm. For the six VIs, the pressure was kept at the order of 10^{-5} Pa. The height of the vacuum interrupters was 471.5 mm and the diameter of the vacuum interrupters was 132 mm. The electrodes of the six VIs were shown in Fig.1. The contact material was CuCr40. The contact diameter was 60mm. The contact surface roughness was 1.6μm. The height of the contact was 15mm. The radius of contact edge was 6mm. And the contact gap was 30mm.

First, we used three VIs to test the influence of switching operation “closing without current / breaking dc current” on the dielectric strength of VIs. Five interrupting current operations, at three conditions of without current, dc current 450 A and dc current 750 A, were carried out on the test VIs No.1, No.2 and No.3 respectively. For the switching operations of dc current 450A and 750A, arc duration was 500ms. Then we used the other three VIs to investigate the influence of switching operations “no operation”, “closing without current / breaking without current” and “closing without current / breaking with 5kA current” on the dielectric strength of the test VIs No.4, No.5 and No.6 respectively. With “no operations” applied, the No.4 VI is attributed as a benchmark for comparison. The switching operation “closing without current / breaking without current” was applied on No.5 VI. And the operation repeated 100 times. The switching operation “closing without current / breaking with 5kA current” was applied on No.6 VI. And the operation repeated 5 times under each polarity.

After a completion of switching operations, the dielectric strength of the six VIs was tested. In our tests the VIs were put vertically to the ground. The stationary contact was in the upper position and the movable contact was in the lower position. The tested vacuum interrupter was put into a porcelain envelope with SF_6 gas as an external insulation of the VI. And the SF_6 pressure in the porcelain envelope was 0.25MPa. The contact gap was adjusted to 30mm through a gap spacing adjuster. The negative polarity BIL voltage (1.2/50μs) were applied to the stationary contact, which was cathode. Dielectric tests were carried out by up-and-down method [8] and ΔV was set as ~4kV. And the injected energy to the electrodes in each shot of impulse voltage application was about 3 kJ. The occurrence of a breakdown was determined by observing the voltage waveforms on a digital oscilloscope.

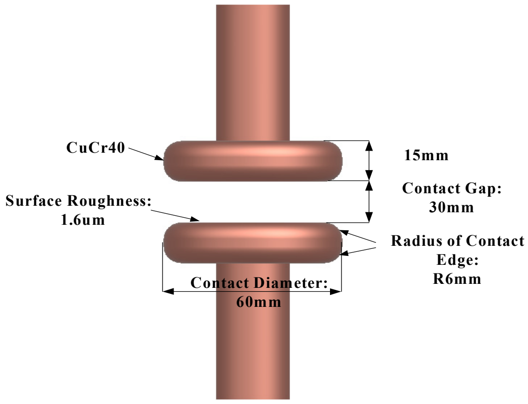

Fig.1 Configuration of plate-to-plate electrodes

III. EXPERIMENTAL RESULTS

A. Conditioning Characteristics

It is well known that the histories of the impulse voltage breakdown voltage in the VIs followed an exponent relationship [9]:

$$U_N = U_1 + U_A (1 - \exp\left(-\frac{n-1}{\tau}\right) \qquad (1)$$

Where U_N, the breakdown voltage at the n^{th} voltage application; U_A=U_L-U_1; U_1, the initial value; U_L, the limit value; τ, the conditioning factor. The higher the τ value is, the slower the conditioning process is. In the equation, U_N and U_L are the breakdown voltage at the n^{th} and the limit value, respectively. In the conditioning process, U_N is increasing as the voltage application N increasing. When the ratio of U_N/U_L is 0.9 and above, the conditioning process is considered entering saturation, which is the criterion of “saturation” in the experiments.

Fig.2 shows a history of breakdown voltage by up-and-down method after switching operations “closing without current / breaking dc current”. In the figure, the breaking currents were 0A, 450A and 750A respectively. The relationships between breakdown voltage and the number of voltage applications were fitted by equation (1). And the results were shown in Table Ⅰ. With no operation (No.1 VI), the conditioning process was fast with conditioning factor τ was 295. With the switching operations of dc current 450A 500ms (No.2 VI), the conditioning factor τ was 306. With the switching operations of dc current 750A 500ms (No.3 VI), the conditioning factor τ was 314.

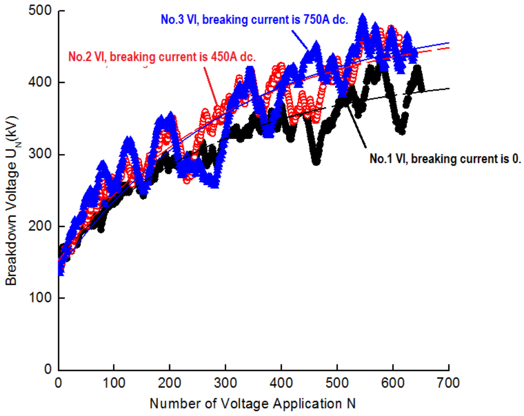

Fig.2. Conditioning process of No.1 VI, No.2 VI and No.3 VI

TABLE Ⅰ. Values of the Parameters for conditioning process

Number of the VIs	Breaking Current of The switching operation	U_1(kV)	U_A (kV)	τ	R-square
1#	no operation	159	257	295	0.92
2#	450A, dc	154	329	306	0.91
3#	750A,dc	141	353	314	0.82

Fig.3 shows a comparison of the influence of switching operations “closing without current / breaking without current” and “closing without current / breaking with 5kA current” on breakdown voltage. The relationships between breakdown voltage and the number of voltage applications were fitted by equation (1). And the results were shown in Table Ⅱ. With no operation (No.4 VI), the conditioning factor τ was 213. With the operations of closing without current / breaking without current (No.5 VI), the conditioning factor τ was 962. With With the operations of closing without current / breaking without current (No.6 VI), the conditioning factor τ was 312.

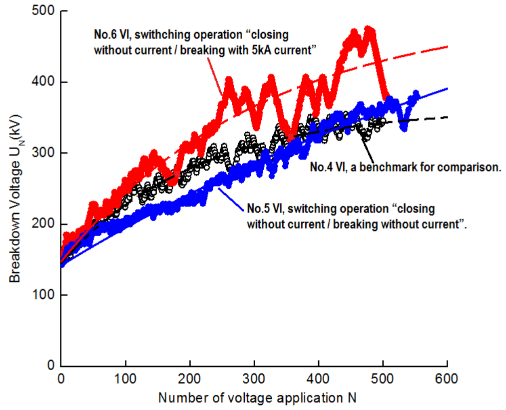

Fig.3. Conditioning process of No.4 VI, No.5 and No.6 VI

TABLE Ⅱ. Values of the Parameters for conditioning process

Number of the VIs	switching operations	U_1(kV)	U_A(kV)	τ	R-square
4#	benchmark	147	364	213	0.96
5#	closing without current / breaking without current	143	678	962	0.90
6#	closing without current / breaking with 5kA current	149	502	312	0.91

B. Saturation Region Characteristics

When a conditioning process entered saturation, the breakdown probabilities of the breakdown voltage were studied for the six VIs. And the breakdown probability followed a 3-parameter Weibull distribution [10].

Table III shows the values of the Weibull parameters for the 3-Parameter Weibull distributions of No.1, No.2 and No.3 VIs. As shown in Table III, the 50% breakdown voltage U_{50} increased from 385kV to 395kV with a dc breaking current 450A. And the U_{50} increased from 385kV to 437kV with the breaking current 750A dc. Table IV shows the values of the Weibull parameters for the Weibull distributions of No.4, No.5 and No.6 VIs after the switching operations, “closing without current / breaking without current” and “closing without current / breaking with 5kA current”. As shown in Table IV, the 50% breakdown voltage U_{50} increased from 340 kV to 362 kV after the switching operation “closing without current / breaking without current”. And the 50% breakdown voltage U_{50} increased from 340 kV to 394 kV after switching operation “closing without current / breaking with 5kA current”.

TABLE III. Values of the Parameters for Weibull Distribution of No.1, No.2 and No.3 VIs

Number of the VIs	Breaking Current of The switching operation	U_0	R-square	U_{50}(kV)
1#	no operation	296	0.99	385
2#	450A, dc	337	0.99	395
3#	750A,dc	365	0.99	437

TABLE IV. Values of the Parameters for Weibull Distribution of No.4, No.5 and No.6 VIs

Number of the VIs	switching operations	U_0	R-square	U_{50}(kV)
4#	benchmark	300	0.99	340
5#	closing without current / breaking without current	328	0.99	362
6#	closing without current / breaking with 5kA current	260	0.97	394

Ⅳ. DISCUSSION

A. Switching Operations Effect on Conditioning Process

Under our experimental conditions, the conditioning factor τ [see Table I. and Table Ⅱ.] increased after the three kinds of switching operations. It means that the conditioning process became slowly after three kinds of switching operations.

The reason could be related to a micro-particle breakdown mechanism. For a contact gap length d $\leqslant 0.5$ mm, instabilities predominantly stemmed from electron emission process. On the other hand, for contact gap length d $\geqslant 5$ mm, micro-particle processes were thought to take over the dominant role [11]. In our experiments, the contact gap was 30mm. So the breakdown mechanism was attributed to a micro-particle initiated mechanism. Kamikawaji et al [12] estimated that there were between 5.7×10^3 and 8.7×10^3 cm^{-2} particles on the contact's surface after contact machining. More micro-particles were generated after the switching operations. So the switching operations increased the vacuum breakdown probabilities by micro-particles mechanism, which were generated by the switching operations [6]. In a conditioning process, a breakdown point located at "breakdown weak point", such as the micro-particles. The conditioning process was completed as virtually all of the breakdown weak points disappeared. So the conditioning process was slowly because more micro-particles generated. It explains that the conditioning process became slowly after the switching operations.

B. Switching Operations Effect on Breakdown Voltage

Toya et al. [10] experimentally studied a statistical property of breakdown voltage of vacuum gaps using parallel plane copper electrodes in a gap length of 3 to 20 mm. They found that the cumulative breakdown probability is expressed in the form of Weibull distribution. Zhang et al. [13] studied the breakdown characteristics in vacuum under a uniform field with a contact gap 6mm. They found that the breakdown probability distribution also followed Weibull distributions when the breakdown voltage saturated. The experimental results for the six VIs after three kinds of switching operations in this paper also supported the previous findings, in which the contact did not endure any switching operations. For the breakdown voltage, after all of the three kinds of switching operations, it was found that it follows a Weibull distribution.

By a comparison of breakdown voltage in the saturation regions for the six VIs, it was found that the 50% breakdown voltage U_{50} increased after the three kinds of switching operations. This can be explained by the contact conditioning effect due to the melting of the contact surface. The formation of surface melting means that the switching operations had a cleaning effect on the contact surface. And the cleaning process always accompanied by the micro-particles produced. But the conditioning process wiped down the micro-particles that are the breakdown weak points. So the breakdown voltage increased after switching current operations.

V. CONCLUSION

The objective of this paper is to experimentally investigate the influence of 3 kinds of switching operations on standard lightning impulse voltage breakdown characteristics of high voltage vacuum interrupters with a contact gap 30mm. The 3 kinds of switching operations are "closing without current / breaking without current", "closing without current / breaking with 5kA current" and "closing without current / breaking dc current". As a result, the following points were indentified:

(1) The three kinds of switching operations have a significant influence on a conditioning process. The conditioning process became slowly after all considered switching operations.

(2) The breakdown voltage probability distribution, after all the three kinds of switching operations, followed the Weibull distribution.

(3) The 50% breakdown voltage U_{50} increased after the switching operations. For the switching operation "closing without current / breaking dc current", the U_{50} increased from 385kV to 395kV with the breaking current 450A dc. And the U_{50} increased from 385kV to 437kV with the breaking current 750A dc. The 50% breakdown voltage U_{50} increased from 340 kV to 362 kV after the switching operation "closing without current / breaking without current". And the 50% breakdown voltage U_{50} increased from 340 kV to 394 kV after switching operation "closing without current / breaking with 5kA current".

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