Breakdown of shield gaps in vacuum interrupters

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Abstract
The objective of this paper is to determine how the high-voltage discharging metal vapour deposited on the nearby ceramic inner surface influences the breakdowns of gaps between centre shield and end shield in vacuum interrupters. Two types of shield materials were selected, namely copper and stainless steel. The end curvature radius of the shield was 3 mm. The distance between the shields could adjust manually from 4 to 8 mm. The distance between the shields and ceramic was 3.5 mm. The negative polarity standard lightning impulse voltage (12/50 μs) was repeated for 900 operations based on an up-and-down method. The experimental results illustrated that the metal deposition layer on the inner surface of the ceramic envelope significantly influenced the breakdown voltage of the shield gaps. At a shield gap distance of \( d = 4 \) mm, the breakdown voltage of the shield gap increased from an initial lower voltage to the saturation voltage by approximately 200 operations. Then, the breakdown voltage decreased to a lower voltage range during only 50 operations, and the breakdown voltage maintained at this lower voltage range until the end of 900 operations. Furthermore, as the shield gap distance increased from \( d = 4 \) to 6 mm and 8 mm, the breakdown voltage also maintained at this lower voltage range. A metal deposition layer was formed on the inner surface of ceramic by repetitive application of the lightning impulse voltage. To analyse the influence of the metal deposition layer, the electric field distributions were calculated for the original vacuum interrupter and the vacuum interrupter with the metal deposition layer on the ceramic inner surface. The simulation results suggested that the metal deposition layer took part in the breakdown path between the shield gaps and deteriorated the insulation performance.

1 | INTRODUCTION

Today, vacuum interrupters (VIs) dominate the field of medium voltage switchgear, which are now entering the higher voltage systems, mostly because of high insulation performance [1–3]. Okubo considered the insulation of VIs into four parts: (1) the insulation between electrodes, (2) the insulation between centre shield and electrodes, (3) the insulation between centre shield and end shield and (4) the internal and external insulation of the ceramic envelope [4].

Many literatures reported the insulation performance of gaps between the centre shield and end shield in VIs [5–9]. Giere et al. found that an optimal radius of the shield to gain the highest insulation performance [5]. The insulation performance of the stainless-steel shield was approximately 15%–40% higher than copper electrode. Schumann et al. proposed a relationship between the breakdown strength and the effective area of the shield gap [6]. However, the metal deposition layer on the ceramic inner surface nearby the shield gap usually influence the insulation between the centre shield and end shield. Both the high-current vacuum arc and high-voltage discharge can produce metal vapour in VIs, forming the metal deposition layer. Kuehn et al. investigated the characterization of the metal vapour deposition layer on VI ceramics inner surface from the high-current interruption [7]. They proposed that the metal deposition layer would...
increase the electric field stress on the ceramics, leading to breakdowns of the VIIs. However, under high voltage, discharges between the centre shield and end shield will also form a metal vapour deposition layer on the ceramic inner surface, and it is still not known this process and its influence on the insulation between the centre shield and end shield.

The objective of this paper is to determine how the high-voltage discharging metal vapour deposited on the nearby ceramic inner surface influences the breakdowns of gaps between centre shield and end shield in VIIs. The results would be useful for designing the shield for VIIs. Furthermore, it is meaningful for higher voltage VI development.

2 | EXPERIMENT SETUP

This study used two samples of VIIs to evaluate the standard lightning impulse voltage breakdown characteristics of the gaps between the centre shield and end shield. Two types of shield materials were used. VI-1 used a pair of stainless-steel shields and VI-2 used a pair of copper shields. Figure 1 shows the configurations of VI-2. For every sample VI, the end curvature radius of both shields was 3 mm. The distance between the shields could adjust manually from 4 to 8 mm, and the distance between the shield and ceramic was 3.5 mm. The heights of the VI and the ceramic are 217.5 and 150 mm, respectively. The vacuum degree was $5 \times 10^{-4}$ Pa. The VIIs were placed into dielectric oil in the experiment to avoid its external flashover. The VIIs were not conditioned before the experiment. A negative lightning impulse voltage ($1.2/50$ μs) was imposed on the moveable shield, and the fixed shield was grounded. An injected energy of each lightning impulse voltage was approximately 10 kJ. The up-and-down method was used [9], and the $\Delta U$ was set to 2 kV. The breakdowns were calculated by observing the voltage waveforms on a digital oscilloscope.

Figure 2 shows the experimental procedure for each VI. First, the gap distance $d$ was set to 4 mm, and 900 times of lightning impulse voltage was applied. Second, the gap distance $d$ was set to 6 mm, and 400 times of lightning impulse voltage was applied. Finally, the gap distance $d$ was set to 8 mm, and 400 times of lightning impulse voltage was applied. Figure 3 shows the voltage waveform of breakdown and no breakdown respectively.

![Figure 1](image1.png)  
**Figure 1** Configuration of the gap between the shields in the vacuum interrupter.

![Figure 2](image2.png)  
**Figure 2** The experiment procedure of each test vacuum interrupter.

![Figure 3](image3.png)  
**Figure 3** The voltage waveform of no breakdown and breakdown. (a) Voltage waveform of no breakdown. (b) Voltage waveform of breakdown.
**Figure 4** The voltage imposed history of vacuum interrupter-1. (a) $d = 4$ mm, (b) $d = 6$ mm and (c) $d = 8$ mm

**Figure 5** The voltage imposed history of vacuum interrupter-2. (a) $d = 4$ mm, (b) $d = 6$ mm and (c) $d = 8$ mm
3 | EXPERIMENT RESULTS

3.1 | Vacuum insulation characteristics with voltage applications

Furthermore, to show the peak values of lightning impulse voltages imposed on VI-1, Figure 4 shows the results of breakdown or no breakdown for every imposed voltage. Figure 4a–c correspond to the three shield gap distances: $d = 4$ mm, $d = 6$ mm and $d = 8$ mm, respectively. In Figure 4a, the negative lightning impulse voltage was imposed on VI-1 for 900 times. By comparing the variation tendency and range, the 900 times of imposed voltages were divided into four sections: section A, section B, section C and section D. The first 150 times of imposed voltages are section A as a conditioning process for the shield gap. At section A, the peak value of lightning impulse voltage is persistently increasing from 30 to 105 kV. Section B is the voltage imposed times between No. 151 and No. 350, at which the imposed voltages entered a saturation region between 90 and 110 kV. Following section B, the imposed voltages sharply decreased to ~50 kV from No. 351 to No. 400 in section C. Last, the imposed voltages maintained in a much lower range between 50 and 70 kV until No. 900 in section D.

In Figure 4b,c, the lightning impulse voltage was imposed 400 times on the shield gap distance $d = 6$ mm and $d = 8$ mm, respectively. The imposed voltages were between 55 and 102 kV at $d = 6$ mm, and between 45 and 90 kV at $d = 8$ mm.

Figure 5 shows the peak values of lightning impulse voltages imposed on VI-2 and the results of breakdown or no breakdown for every imposed voltage. Figure 5a–c correspond to the three shield gap distances of $d = 4$ mm, $d = 6$ mm and $d = 8$ mm, respectively. In Figure 5a, the negative lightning impulse voltage was imposed on VI-2 for 900 times. The 900 times of imposed voltages were also divided into four steps: section A, section B, section C and section D. The first 200 times of imposed voltages are section A, as a conditioning process. At section A, the peak value of the lightning impulse
TABLE 1 The gap distances, sections and corresponding $U_0$, and the parameters of three-parameter Weibull distribution

| VI  | Gap distance (mm) | Sections | Number of statistics | $U_0$ (kV) | $U_{90}$ (kV) | $U$ (kV) | $m$ | R-Square |
|-----|-------------------|----------|----------------------|------------|--------------|---------|-----|----------|
| VI-1| 4                 | Section B No. 151–350 | 200         | 52         | 96.0         | 98.2    | 7.20| 0.988    |
|     | 4                 | Section D No. 401–900  | 500         | 40         | 63.2         | 65      | 4.74| 0.998    |
|     | 6                 | No. 1–400             | 400         | 53.1       | 70.0         | 72.9    | 2.30| 0.999    |
|     | 8                 | No. 1–400             | 400         | 50         | 75.5         | 78.6    | 3.23| 0.999    |
| VI-2| 4                 | Section B No. 201–300  | 100         | 50.2       | 89.8         | 92.7    | 23.68| 0.991    |
|     | 4                 | Section D No. 701–900  | 200         | 46.4       | 61.3         | 63.6    | 2.52| 0.997    |
|     | 6                 | No. 1–400             | 400         | 44         | 65.0         | 68.3    | 2.45| 0.999    |
|     | 8                 | No. 1–400             | 400         | 36.3       | 66.0         | 72.3    | 1.90| 0.998    |

Abbreviation: VI, vacuum interrupter.

Voltage persistently increases from 30 to 105 kV. Section B is the times between No. 201 and No. 300 at which the imposed voltages entered a saturation region between 70 and 110 kV. After section B, the decreasing of imposed voltage is obvious. However, the imposed voltages sharply decreased and sharply increased in a significant variation range until the No. 700. Thus, the times between No. 301 and No. 700 were divided into section C. The last 200 times of imposed voltages are section D, in which the lightning impulse voltages stable between 45 and 80 kV.

In Figure 5b,c, the lightning impulse voltage was imposed 400 times for the shield gap distance $d = 6$ mm and $d = 8$ mm, respectively. The imposed voltages were between 45 and 75 kV for $d = 6$ mm, and between 45 and 90 kV for $d = 8$ mm.

3.2 | The breakdown probability and three-parameter Weibull distribution for different applied voltages

For VI-1 and VI-2, the cumulative breakdown probability was calculated at gap distances $d = 4$ mm, $d = 6$ mm and $d = 8$ mm respectively. The three-parameter Weibull distribution was used to analyse the breakdown probability distribution. Equation (1) gives the relationship between the cumulative breakdown probability $F(U)$ and the imposed voltage $U$ by a three-parameter Weibull distribution [10,11].

$$F(U) = 1 - \exp \left[ - \left( \frac{U - U_0}{U' - U_0} \right)^m \right]$$

$F(U)$ means the cumulative probability at the imposed voltage $U$. $U_0$ is the voltage at which the breakdown probability is zero. $U'$ is the scale parameter for which $F(U') = 1-e^{-1} = 0.632$, and $m$ is the shape parameter being a measure of data dispersion.

To gain these three parameters, $U_0$, $U'$ and $m$, the scatter data were first plotted according to the measured breakdown voltages and the corresponding probability values. The cumulative breakdown probability Weibull distribution curve was then fitted to the scatter data. Last, the three parameters were obtained from the cumulative breakdown probability Weibull distribution curve.

Figure 6 shows the cumulative breakdown probability distribution and the Weibull fitting curves of VI-1 at gap distances $d = 4$, 6 and 8 mm. To distinguish the differences of the imposed voltages between section B and section D at gap distance $d = 4$ mm, the breakdown probability and the three-parameter Weibull distribution were calculated for both sections. Figure 6a,b show the cumulative breakdown probability distribution and the Weibull fitting curves for section B and section D, respectively. For VI-2, the cumulative breakdown probability distribution and the Weibull fitting curves were also calculated, but they are not shown in the figures.
Table 1 shows the parameters of the three-parameter Weibull distribution for VI-1 and VI-2. Furthermore, Table 1 also shows the R-squares that were used to evaluate the goodness of fitting. The R-square is the goodness of fit statistics, and can be calculated by using Equation (2).

$$R^2 = 1 - \frac{RSS}{TSS} \tag{2}$$

RSS is the residual sum of squares, and TSS is the total sum of squares.

3.3 The metal deposition layer and its elements

A metal deposition layer was found on the ceramic inner surface in both VI1s after being dissected. Figure 7 shows the metal deposition layer on the ceramic surfaces of VI-1 and VI-2. For VI-1, the metal deposition layer is nearly a
ring, approximately 15–25 mm wide. For VI-2, the metal deposition layer was only a partial ring, approximately 15–25 mm wide. The metal deposition layers were located surrounding the gap between the centre shield and end shield for both VIs.

Furthermore, scanning electron microscope and energy dispersive spectrometer analyses were conducted to observe the metal deposition layer [12]. Figure 8 shows the microstructure of metal deposition. Figure 9 shows the energy spectrum of the metal layer from EDS. There were three elements on the ceramic of VI-1, namely Fe, Cr and Ni, respectively. On the other hand, only Cu was found on the ceramic of VI-2. The deposited elements corresponded to the shield material. Therefore, it could be supposed that the metal layer was gradually deposited by the metal vapour evaporated from the high-voltage discharge between the shields.

4 | ANALYSIS AND DISCUSSION

The \( U_0 \) and \( U_{50} \) were calculated and shown in Table 1. In addition, the \( U_0 \) and \( U_{50} \) have used to evaluate the insulation performance of the shield gaps. The following three points were abnormal:

i. At \( d = 4 \) mm, the \( U_0 \) and \( U_{50} \) of section B are higher than the \( U_0 \) and \( U_{50} \) of section D for both VIs.

ii. The \( U_{50} \) at \( d = 6 \) mm or \( d = 8 \) mm are lower than the \( U_{50} \) of section B at \( d = 4 \) mm for both VIs. Moreover, the \( U_{50} \) at \( d = 6 \) mm and \( d = 8 \) mm only slightly increased relative to the \( U_{50} \) of section D at \( d = 4 \) mm for both VIs.

iii. The \( U_0 \) at \( d = 6 \) mm or \( d = 8 \) mm only slightly increased relative to the \( U_0 \) of section D at \( d = 4 \) mm for VI-1. Furthermore, the \( U_0 \) at \( d = 6 \) mm or \( d = 8 \) mm are even lower than the \( U_0 \) of section D at \( d = 4 \) mm for VI-2.

These three points could be explained by the influence of the metal deposition layer on the ceramic inner surface. To analyse the influence of metal deposition layer on the \( U_0 \) and \( U_{50} \) of both VIs, the electric field distribution was calculated for the original VI without the metal deposition layer and the VI with the metal deposition layer on the ceramic inner surface.

Figure 10 shows a VI model with the metal deposition layer on the ceramic inner surface. The VI model was identical to the samples in the experiment. The shield gap distance was set to 4 mm. The imposed voltages were set identical to the \( U_{50} \) of VI-1 at section B and section D with \( d = 4 \) mm in Table 1, which were 96 and 63.2 kV, respectively. The high voltage was imposed on the moveable terminal, and the fixed terminal was grounded. The metal deposition layer was set to a floating potential at 0.1 mm thickness and 20 mm high. The metal deposition layer was embedded in the ceramic surface [13].

**FIGURE 11** The electric field distribution. (a) \( U_m = 96 \) kV, without metal layer, (b) \( U_m = 96 \) kV, with metal layer, (c) \( U_m = 63.2 \) kV, without metal layer and (d) \( U_m = 63.2 \) kV, with metal layer.
Figure 11 shows the electric field distribution of VI's with or without the metal deposition layer. Figure 11a,b show the electric field distribution of VI without the metal deposition layer when the imposed voltage was 96 kV. Figure 11c,d show the electric field distribution of VI with the metal deposition layer on the ceramic when the imposed voltage was 63.2 kV.

For Figure 11a,d, the applied voltages were 96 and 63.2 kV, respectively, but the cumulative breakdown probability is equal to 50%. Therefore, an equal breakdown probability appeared when the different voltages were imposed on two identical gaps. The difference between the two gaps was the metal deposition layer. Figure 11d shows that the metal layer on the ceramic inner surface increased the electric field stress of the ceramic inner surface, leading to a decrease in breakdown voltage.

Figure 12 shows two lines. One is named surface, and other was named gap, and both were 22 mm long. Furthermore, Figure 13 shows the electric field stress along two lines, surface and gap. Figure 13a shows the electric field stress distribution of the shield gap without the metal deposition layer on the ceramic inner surface. It shows that the maximum electric field stress of the shield gap is 30 kV/mm, and it locates at the shield's end part. The maximum electric field stress on the ceramic inner surface is 9 kV/mm. However, Figure 13b shows the electric field stress of the shield gap with the metal deposition layer on the ceramic inner surface. The maximum electric field stress $E_{\text{max}}$ is 18.5 kV/mm, and it locates at the shield end's end part too. However, the electric field stress of the metal layer on the ceramic inner surface increased to 17.5 kV/mm. Thus, the metal deposition layer on the ceramic inner surface significantly increased the electric field stress of the ceramic inner surface.

Furthermore, by comparing the positions and values of the maximum electric field stress of the two cases shown in Figure 13a,b, Figure 14 proposes the breakdown paths. For the shield gap without metal deposition layer on the ceramic
inner surface, the breakdown could start from one shield’s end part to another shield’s end part directly. However, for the shield gap with the metal deposition layer on the ceramic inner surface, the breakdown could start from one shield to the metal deposition layer on the ceramic inner surface, then along the metal deposition layer and back to the other shield.

The change in the breakdown paths could explain the previous three points. Once a metal deposition layer was formed on the inner surface of the ceramic, the breakdown kilo voltages were defined by the alternative breakdown path, so that the \( U_0 \) and \( U_{50} \) of section B are much higher than the \( U_0 \) and \( U_{50} \) of section D for both VI s at \( d = 4 \) mm. The \( U_0 \) and \( U_{50} \) at \( d = 6 \) mm or \( d = 8 \) mm are much lower than the \( U_0 \) and \( U_{50} \) of section B at \( d = 4 \) mm for both VI s. Furthermore, the \( U_0 \) and \( U_{50} \) at \( d = 6 \) mm and \( d = 8 \) mm only slightly increased relative to the \( U_0 \) and \( U_{50} \) of section D at \( d = 4 \) mm for both VI s.

5 | CONCLUSION

In this paper, we investigated how the high-voltage discharging metal vapour deposited on the ceramic inner surface influence the insulation performance between centre shield and end shield in VI s. As a result, the following points were drawn:

i. After approximate three hundred times of lightning impulse voltage discharge, the metal vapour deposition layer on the ceramic inner surface significantly influence the insulation performance between centre shield and end shield.

ii. Even the gap distance kept fixed, the \( U_0 \) and \( U_{50} \) of gap between centre shield and end shield decreased by the influence of metal deposition layer on the ceramic inner surface. Furthermore, the \( U_0 \) and \( U_{50} \) only slightly increased by increasing of the shield gap distance.

iii. The metal deposition layer on the ceramic inner surface took part in the breakdown path between centre shield and end shield. It deteriorated the insulation performance.

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