Introduction to Surface Insulation Design Methods for Ceramic Materials Used in Vacuum Interrupters (VIs)

Hideaki Fukuda,
Kenta Yamamura

Keywords VI, Higher voltages, Surface discharge, Triple junction, Shield

Abstract

Improved dielectric strength of vacuum interrupters (VIs) is essential for increasing the voltage and compact design of vacuum circuit breakers (VCBs). Surface insulation design can be difficult to solve using existing analytical techniques alone.

Therefore, with the aim of obtaining design guidelines for VI surface insulation, focusing on the shield structure for alleviating the electric field at the brazed joint between metal parts and ceramics, surface flashover tests were conducted and the results were evaluated. The maximum value of the surface flashover withstand voltage was identified for a fixed ceramic size. This maximum value is considered to be the boundary condition where the initiation point of surface discharge transitions from the brazed joint to the shield, and these experimental results are expected to provide useful guidelines for VI insulation design.

1 Preface

From the perspective of achieving carbon neutrality, expectations are rising for the application of vacuum circuit breakers (VCBs), which do not use sulfur hexafluoride (SF_6) gas, a greenhouse gas, to even higher voltage systems. As voltage increases, insulation requirements become stricter, and high electric fields are generated in the vacuum interrupter (VI) installed inside the VCB tank. One of the insulation challenges to be solved is the suppression of surface discharge generated inside the VI.

Ceramic materials for VIs have a metal layer called a metallized layer. The boundary between the metallized layer and the ceramic, including the vacuum, forms a triple junction (TJ), where the electric field tends to concentrate, reducing the surface insulation strength. Therefore, in many VIs, shields are placed as a means to mitigate the electric field near the TJ, and the shield structure is optimized using electric field analysis software. However, the shape of the interface between the metallized layer and the ceramics is complex, and even slight differences in shape significantly alter the electric field analysis values. Therefore, it is difficult to completely reproduce the shape near the TJ through analysis. Consequently, solving the problem through experimental evaluation, in addition to existing analytical techniques, is necessary.

Therefore, we made an experimental sample that partially simulated the surface area of VI and obtained the surface discharge characteristics when the shield structure was changed. This paper presents an example of the obtained characteristics.

2 VI Structure

Fig. 1 shows a schematic cross-section of VI, and Fig. 2 shows a scanning electron microscope

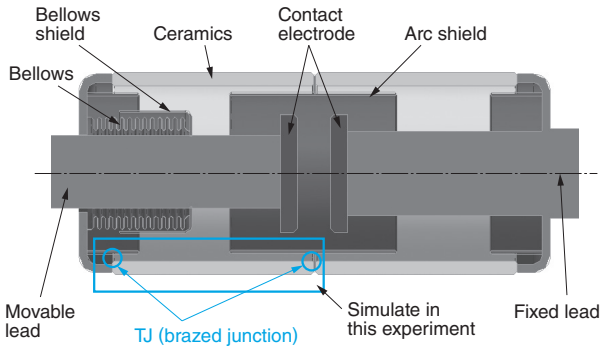


Fig. 1 VI Schematic Cross Section

TJ is formed on both end surfaces of ceramics.

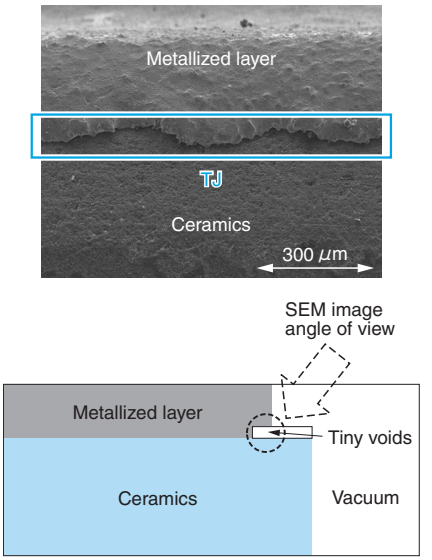


Fig. 2 SEM Images near TJ

The electric field is concentrated in the tiny voids at the interface between the metallized layer and ceramics.

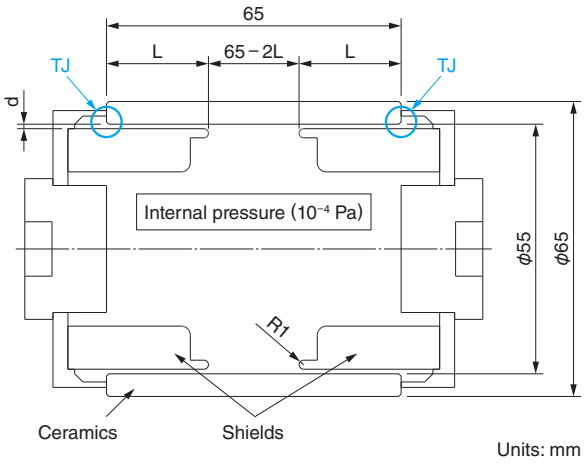


Fig. 3 Experiment Sample Schematic Cross Section

An experiment sample simulating the surface area of VI was produced. By brazing in a vacuum furnace, the interior is kept in a high vacuum state.

(SEM) image near the TJ. There are minute voids at the interface between the metallized layer and the ceramics, and a shield is placed because the electric field is concentrated near these voids. In this experiment, an experimental sample simulating the area enclosed by the blue frame in Fig. 1 was made.

3 Experimental Sample

Fig. 3 shows a schematic cross-section of the experimental sample. The sample was made by vacuum brazing, and the interior was maintained in a high vacuum state on the order of 10^{-4} Pa.

Table 1 Shield Size Details

Samples were produced under a total of 19 conditions where the length L from TJ and the gap D between ceramics were different.

Gap d (mm)	Shield length L (mm)
2	1.5, 4.5, 7.5, 9.5, 13.5, 22.5, 27.5
4	1.5, 4.5, 7.5, 13.5, 17.5, 27.5
6	4.5, 7.5, 9.5, 13.5, 17.5, 27.5

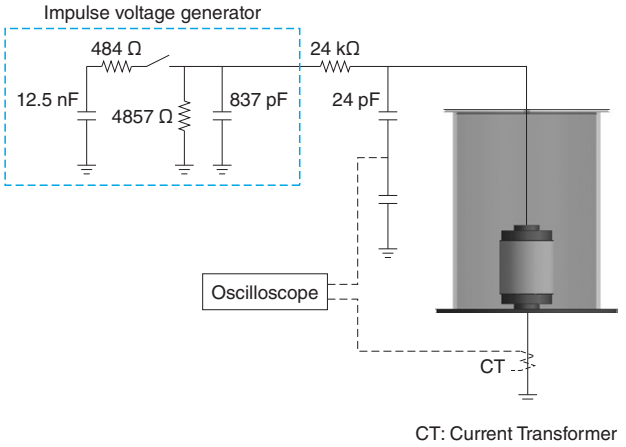


Fig. 4 Experiment Circuit

An impulse voltage with a negative polarity was applied to the experiment sample, and surface discharge was performed inside the sample.

Stainless steel (SS304) was used as the shielding material. Shields of the same structure were placed at both ends of the ceramic, and the length L from the TJ to the tip of the shield and the gap d between the shield and the ceramic were used as parameters. The distance between shields, 65 − 2L, is defined as the creepage distance. Table 1 shows the detailed dimensions of the experimentally tested shields. The evaluation was performed under a total of 19 conditions based on the combination of gap d and shield length L.

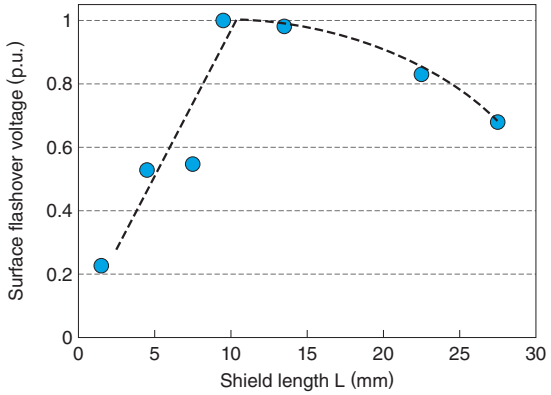
4 Experimental Method

Fig. 4 shows the experimental circuit. A negative impulse voltage was applied to one end of the sample, and repeated surface discharge was generated inside the sample. The area around the sample was filled with insulating oil. In addition, to prevent contamination of the inner surface of the ceramic due to repeated surface discharge, a 24 kΩ resistor was placed between the voltage divider and the impulse device to limit the current during discharge.

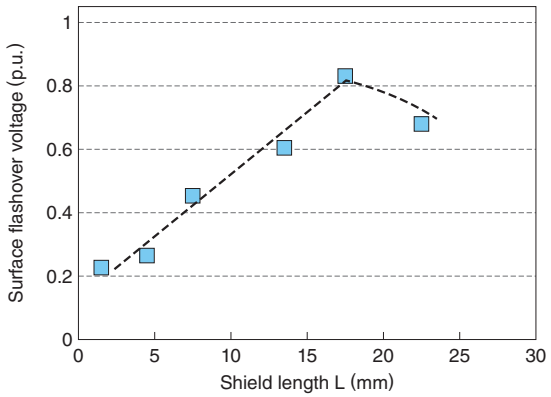
5 Experimental Results and Discussion

Fig. 5 shows the surface discharge test results for each gap d between the shield and ceramics, as well as the shield length L. Table 2 shows the maximum value for each gap d and the shield length L. At d = 2 mm, the surface discharge voltage reached a maximum value at L = 9.5 mm. At d = 4 mm, there was also a maximum value, similar to the case of d = 2 mm, but the L at that time was longer at 17.5 mm, and the maximum value itself was lower than at d = 2 mm. This is thought to be because the electric field near the TJ was mitigated by the shield. Furthermore, the reason why the surface discharge voltage decreased is thought to be because the creepage distance between the shields was reduced due to the shield being too long. In other words, it can be said that at L = 9.5 mm for d = 2 mm, and at L = 17.5 mm for d = 4 mm, the starting point of surface discharge shifted from the TJ to the shield. On the other hand, in the case of d = 6 mm, no maximum value was observed, and the creepage discharge voltage remained in a lower range compared to other conditions. This is thought to be because the electric field relaxation effect near the TJ by the shield was weak, and creepage discharge originating from the TJ continued to occur regardless of the shield structure.

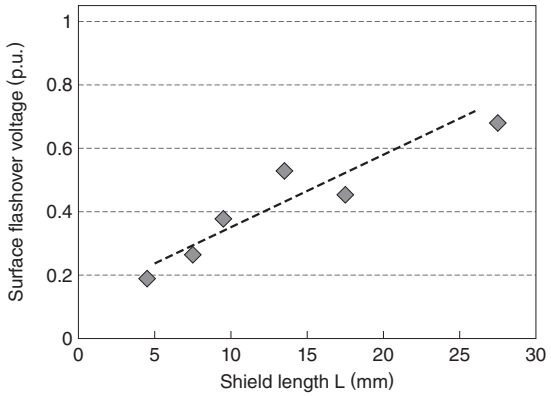
Fig. 6 summarizes the conditions in which the surface discharge voltage increased with increasing shield length L, expressed as the dimension



(a) d = 2 mm



(b) d = 4 mm



(c) d = 6 mm

Fig. 5 Surface Flashover Test Results

The results of the surface discharge test for the shield length L for each gap d are shown.

Table 2 Maximum (Maximum) Value for Each Gap d and Shield Length L

The maximum (maximum) value for each interval d and the shield length L at that time were summarized.

Gap d (mm)	Maximum (maximum) value of surface flashover voltage (p.u.)	Shield length L (mm)
2	1.00	9.5
4	0.83	17.5
6	0.68	27.5

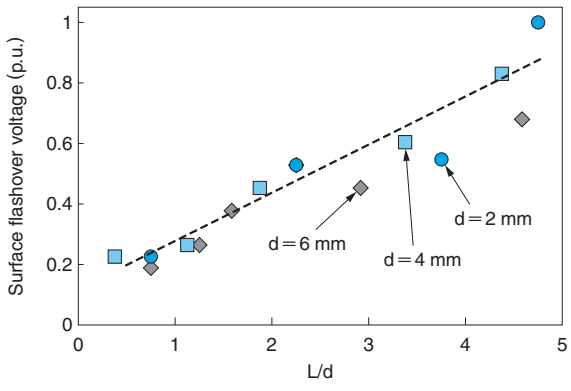


Fig. 6 Relationship between L/d and Surface Discharge Voltage

When the surface discharge voltage rises due to an increase in L/d, it means that surface flashover starting from TJ has occurred.

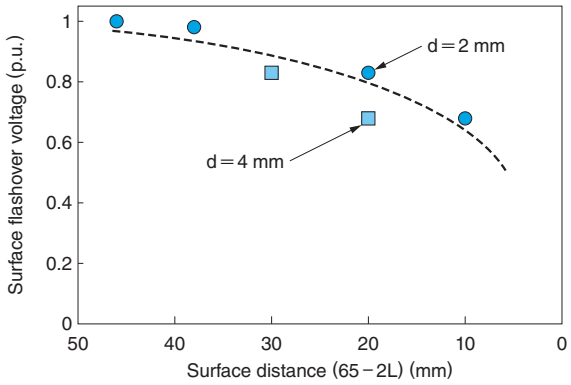


Fig. 7 **Relationship between Surface Distance and Surface Flashover Voltage**

The fact that the surface flashover voltage also drops due to the shortening of the crevice distance means that surface flashover starting from the shield has occurred.

ratio L/d. An increase in L/d means that the creepage distance decreases, and in shield conditions where the surface discharge voltage increases during this process, it is thought that the discharge origin is still at the TJ. Fig. 7 shows the relationship between creepage distance and surface discharge voltage. Conditions in which the surface discharge voltage decreased with increasing L are summarized as the creepage distance. In this process, it is thought that the discharge origin has already shifted to the shield. Furthermore, in the results shown in Fig. 5, the maximum value was higher when d = 2 mm than when d = 4 mm. Considering this from the perspectives of L/d and creepage distance, it can be explained that a smaller d allows for the mitigation of the electric field near the TJ with the minimum necessary L, and the remaining space is used to secure the creepage distance.

Based on these results, when considering the shield structure of VI from the perspective of insulation design, it is necessary to first find the boundary conditions under which the discharge initiation point transitions from the TJ to the shield. In particular, the gap d between the shield and the ceramics is an important factor in extracting the maximum surface insulation capability under conditions where the size of the ceramics is limited.

6 Postscript

Regarding the electric field relaxation method near the TJ of ceramic materials with complex shapes, important guidelines were obtained for maximizing surface insulation capability within the limited size of the ceramics.

・All product and company names mentioned in this paper are the trademarks and/or service marks of their respective owners.