Effects of Roughening Insulator Surface on Charging and Flashover Characteristics of a Long Glass Insulator in Vacuum

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To develop high voltage VCB’s with high reliability and compactness, we have been studying charging and flashover characteristics of insulators in vacuum. In the previous studies, we have clarified that roughening insulator surface is effective to mitigate the charging and to improve the insulation strength. Since the former investigations are limited in insulator length to be less than or equal to 10 mm, we have investigated to confirm the effects for longer specimens up to 50 mm in the present study.

We conducted charge measurements, flashover tests and calculation of surface charge distribution under DC voltage excitation. The insulator was borosilicate (Pyrex®), and was in the shape of a right cylinder. The side surface of the specimen was polished to have an average roughness of sub microns or roughened up to several microns. The charging characteristics of insulators were investigated by using an electrostatic probe, which was embedded in the plane cathode and allowed a time resolved measurement of the charging process.

Figure 2 shows the influence of surface roughness on charging. For simplicity, only the results for insulator lengths of 10 and 50 mm are compared. The figure clearly shows that the charge magnitude decreases with the increase in roughness even in the case when the insulator is 50 mm long.

The flashover voltages obtained for 10, 20, 30 and 50 mm specimens are summarized in Fig. 2 as a function of surface roughness. It is seen at each length that the flashover voltage increases with the roughness. As the flashover in vacuum is preceded by surface charging, the increase in flashover voltage with surface roughness is consistent with the results in Fig. 1.

From these results, we have confirmed that roughening the insulator surface is effective for a wide range of insulator length in order to mitigate the surface charging and to improve the insulation strength in vacuum.

The surface charging is substantially suppressed at a roughness of \( R_a \geq 3 \, \mu m \). These results are useful not only for high voltage VCB’s but also for other equipment that uses high voltage in vacuum such as particle accelerators.
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We have studied charging and flashover characteristics of a glass insulator with 0.3 - 50 mm long under DC voltage excitation in vacuum. We conducted flashover tests, charge measurements and calculation of surface charge distribution. The insulator was borosilicate, and was in the shape of a right cylinder. The side surface of the specimen was polished to have an average roughness of sub microns or roughened up to several microns. The charging characteristics of insulators were investigated by using an electrostatic probe, which was embedded in the plane cathode and allowed a time resolved measurement of the charging process. As a result, we have confirmed that roughening the surface mitigates the surface charging and thus improves the insulation strength for a specimen up to 50 mm in length. These results are useful not only for high voltage VCB’s but also for other equipment that uses high voltage in vacuum such as particle accelerators.

Keywords: flashover, charging, Pyrex® glass, PMMA, long insulator, DC, vacuum.

1. Introduction

High voltage VCB’s (Vacuum Circuit Breakers) are considered as an alternative of GCB’s (Gas Circuit Breakers) in order to reduce SF6 that has a high global warming potential(1). For developing high voltage VCB’s with high reliability and compactness the insulation design of the vacuum bottle made of glass or ceramics is of importance, since it is widely recognized that insulation design for flashovers along solid insulators is critical.

Major theories of flashover mechanisms in vacuum have been summarized in literatures(2)(3) although there are some controversies in the understanding of the mechanism. Based on our previous studies with pulsed(4), DC(5) and AC(6) voltages it is believed that the charging of an insulator surface occurs through a process called Secondary Electron Emission Avalanche (SEEA), and in most cases it precedes flashover in vacuum. That is, the flashover in vacuum is triggered by surface charging which starts from electrons released from the triple-junction on cathode. Those electrons hit on the insulator, and release the secondary electrons. Causing avalanche-like multiplication along the surface, they travel toward the anode. In most cases, the result is the surface electrification of positive polarity. The accumulated positive charge enhances electrical field at the triple-junction and extracts further electrons from cathode.

To mitigate surface charging and improve flashover strength in vacuum, several methods or techniques have been developed:

- Minimizing secondary electron emission yield by coating TiN(7) or doping Cr2O3(8).
- Arranging the direction and distribution of electrical field by changing the shape of an insulator(9).
- Reducing electrical field near the triple-junction by changing the shape of a cathode(10).
- Roughening the insulator surface(4)-(6)(11).

Furthermore, we have developed a simple method:

- Rroughening the insulator surface (4)-(6)(11).

The effectiveness of the fourth method can be attributed to the fact that surface irregularities prevent the migration of electrons along insulator surface. That is, since the electrons in vacuum...
during the charging process have less than 1 µm in hopping height measured from the surface\(^7\), the protrusions of the surface act as barriers against those hopping electrons as shown in Fig.1. These are our former results obtained for comparatively short test insulators of less than or equal to 10 mm in length.

The method is very simple and free from increasing volume or weight of an insulating spacer used in vacuum (imagine angled insulators\(^9\), for example). However, it is necessary to investigate and confirm the effects for longer test insulators in order to apply the method for practical apparatus.

The purpose of the present study is to confirm the effectiveness of roughening insulator surface for longer specimens and to obtain useful data for designing a high voltage vacuum bottle. The paper presents the results of experimental investigations on charging and flashover characteristics for a glass insulator up to 50 mm in length.

2. Experimental

The applied voltage is a ramped DC, and the vacuum vessel was evacuated down to \(10^{-3}\) or \(10^{-4}\) Pa. Since the setup and experimental procedures are the same as that we have used for the previous studies\(^4\)-\(^6\)-(\(^12\)), we briefly explain important items.

2.1 Insulators

The test insulator was made of borosilicate (Pyrex\(^8\)), and was in the shape of a right cylinder with 54 mm in diameter. The length \(l\) varies from 0.3 mm up to 50 mm. High voltage performance of our vacuum vessel limited the maximum length examined.

The surface of Pyrex\(^8\) had an average roughness \(R_a\) of 0.03, 1.2, 2.6 or 3.1 µm (four classes). The specimen with 0.03 µm roughness, optically smooth surface, was polished by using buff. Other insulators were roughened by using emery wheel having various grain sizes. Roughness larger than 3.1 µm is difficult to process by the same method, since it would form severe cracks on the surface and at edges at both ends.

2.2 Surface Charge Measurement

Figures 2 (a) and (b) show arrangement of electrodes, an insulator and a probe. The electrodes are made of aluminum, and are in a disk type with 130 mm in diameter and 24 mm in thickness. The probe is a ring shaped part isolated from the cathode and is located coaxially with a cylindrical specimen as shown in Fig. 2 (a). We grounded the probe through a charge measuring capacitor and its terminal voltage is transmitted to a digital oscilloscope via an amplifier that has very high input impedance (5 G-ohm) and low out put impedance (50 ohm)\(^10\).

As the insulator covers entire surface of the probe facing to the high voltage electrode, the probe hardly acquires true charge through vacuum or along the insulator surface. The probe signal and the applied voltage were measured simultaneously by using the oscilloscope. We converted the probe signal into electric field strength \(E_{TJ}\), which is the sum of the geometrical field component \(E_g\) and the surface charge component \(E_s\):

\[
E_{TJ} = E_g + E_s. \tag{1}
\]

We evaluated the geometrical field from the oscillograph of applied voltage as

\[
E_g = V_{ap} / d, \tag{2}
\]

where, \(V_{ap}\) is the applied voltage and \(d (= l)\) the electrode separation. When we compared the oscillograph of probe signal and applied field, which is obtained by Eq. (2), at a voltage low enough to suppress charging, e.g. 1 kV, there was a small difference due to conduction current and polarization of dipoles in the Pyrex\(^8\) specimen. When PMMA and fused quartz were examined\(^12\), we did not see this difference since these materials had much higher bulk resistivity and little dipoles.

2.3 Flashover Test and Probe Measurement

Figure 3 shows flashover histories obtained for different surface roughness at 50 mm in length. For each of the specimen we measured 30 flashover voltages. This test includes the neutralization of residual surface charge by introducing small amount of air in the chamber after every 10 flashovers. We consider the first and second groups of the executions (20 flashovers) as conditioning process and the voltages for last 10 flashovers are averaged.

Since our probe circuit is fragile to the surge voltage that is induced at the instance of flashover event, we have to be careful to avoid any undesirable flashovers during the charge measurement. Because of this reason, the probe measurement was conducted after the flashover test, where we applied a voltage well below the minimum voltage that appears in each flashover history.

![Fig. 2. Arrangement of electrodes, a probe and an insulator](image-url)
3. Charging Characteristics

3.1 Charge Magnitude with Smooth Surface  
Figure 4 shows an example of probe measurement when a Pyrex® insulator, having 50 mm length and 0.03 μm surface roughness, is examined. The probe signal increases with the increase in the applied voltage. The highest applied voltage in this case is 40 kV, at which the voltage is turned off. After the voltage removal, the surface charge is neutralized by a silent discharge that occurs when a small amount of air is introduced in the vacuum vessel [12].

As mentioned in subsection 2.2, the probe signal includes conduction and polarization components other than $E_s$ and $E_g$. Therefore, the probe signal shows a certain amount of value even after the neutralization. In the case that PMMA or fused quartz specimen was examined, the probe signal usually reduced to zero after the neutralization.

The surface charge component $E_s$ for Pyrex® insulator is determined from the sharp reduction when the silent discharge occurs, as shown in Fig. 4.

To evaluate the magnitude of accumulated charge on the surface, we define a normalized electric field $ETJ/Eg$ and call this index as the surface charge magnitude hereafter. The charge magnitudes so obtained for different insulator lengths are shown as a function of insulator length in Fig. 5. In the figure, the measured magnitude is compared with calculated one, which will be explained later in section 4.

The measured charge magnitude in Fig. 5 increases with insulator length, but it saturate as the insulator increases in its length although the charge magnitude shows a little increase again at $l \geq 30$ mm.

3.2 Effect of Roughness on Charge Magnitude  
Figure 6 shows the influence of surface roughness on charge magnitude. For simplicity, only the data for 10 and 50 mm insulators are plotted. The figure clearly shows that the charge magnitude decreases with the increase in roughness even in the case when the insulator is 50 mm long. The approximate roughness at which charging is effectively suppressed, i.e. $ETJ/Eg = 1$, is 3 μm when the length is 10 mm. The charging for 50 mm insulator is substantially suppressed at 3 μm, however, the roughness should be somewhat larger than 3 μm in order to realize $ETJ/Eg = 1$. The insulator of 20 mm length showed similar charging characteristics with that of the 10 mm insulator, and 30 mm insulator with that of the 50 mm insulator as indicated by broken lines.

From these results, we have confirmed that roughening the
insulator surface is effective to mitigate the surface charging in vacuum for a long insulator up to 50 mm.

4. Discussion on Charging Characteristics

4.1 Saturation of Calculated Charge Magnitude

In order to analyze the charging characteristic with the smooth surface shown in Fig. 5, we calculated the theoretical charge magnitude relying on the SEEA mechanism.

In the calculation, we firstly calculated the distributions of surface charge for various insulator lengths. The density and its distribution of accumulated charge can be calculated taking the secondary electron emission characteristic of the insulator and the electric field into account (13)-(15). The calculated distribution is at an equilibrium state, which is defined as the state at which the number of secondary electrons from a point over the insulator surface equals to the number of incident electrons. Secondary, we analyzed the electric field on the cathode taking the calculated charge distribution into account, and thus the magnitude of probe signal \( E_T = E_s + E_g \). Refer to the reference (16) for more details.

Figure 7 shows the calculated surface charge distributions for various insulator lengths as a function of normalized distance from cathode. In each insulator length the applied voltage \( V_{ap} \) is selected to keep the applied electric field constant \( \left( V_{ap} / d = 2 \text{kV/mm} \right) \). From the calculated charge distributions, one note that the charge density in the midst of the insulator becomes low as the insulator length increases. This is caused by the non-uniformity of the geometrical electric field distribution along the insulator surface, where the non-uniformity of the field occurs because the size of test electrodes is the same irrespective of insulator length.

From above mentioned result, we understand the saturation of calculated charge magnitude shown in Fig. 5 is attributed to the reduction of surface charge amount. Also, when a long insulator is examined, charges accumulated far from the probe may cause weak probe signal.

4.2 Discrepancy between Measured and Calculated Charge Magnitudes

The measured charge magnitude in Fig. 5 coincides with calculated one when the insulators are short; up to 10 mm. More detailed comparison in this condition is found in the Ref. (16). For longer insulators, however, the measured magnitudes are much smaller than calculated ones. The reason of this discrepancy is not clear at present, however, one of the possible reasons is discussed below.

For a certain insulator length, it is reasonable to take normalized probe signal \( E_s/E_g \) or \( E_T/E_g \) as the magnitude of accumulated charge, since the charge density is theoretically proportional to the applied electrical field (13)(14). This is valid as far as the equilibrium state is achieved all over the surface.

In our experiment the applied field becomes low as the insulator length increases, since the applied voltage height is limited as stated in the subsection 2.3; \( E_s \) equals to 2 kV/mm at \( l = 10 \text{mm} \) and 0.8 kV/mm at \( l = 50 \text{mm} \) (Refer to Fig.5 for the limits of applied voltages.) This might stop the charging on the way to the anode as schematically illustrated in Fig. 8 (Charging starts from cathode side surface and progresses toward anode (15)). If this happens, the charge will not cover whole insulator surface and this will result in reduced probe signal. We need further investigation on this point including a direct charge distribution measurement.

5. Flashover Characteristics

5.1 Flashover Voltage

As explained in the subsection 2.2, we averaged the last 10 data of each flashover history. The averaged flashover voltages obtained for 10, 20, 30 and 50 mm specimens are summarized in Fig. 9 as a function of surface roughness. The error bar for each datum indicates the lowest and highest flashover voltages in the 10 flashover histories. It is seen in each length that the flashover voltage increases with the roughness. As the flashover in vacuum is preceded by surface charging, the increase in flashover voltage with surface roughness is consistent with the results in Fig. 6.

Figure 10 shows flashover voltages as a function of insulator length. The Figure includes data obtained for specimens with shorter length \( l = 0.3, 1, 3, 5 \text{mm} \). In this Figure, only the flashover voltages for \( R_s = 0.03 \text{ and } 3.1 \mu \text{m} \) are compared for simplicity. In each roughness the flashover voltage increases, with distinct saturation, as the insulator length increases. Note that, for insulators with length up to 50 mm, the flashover voltage with approximately 3 \( \mu \text{m} \) roughness is as high as twice, or even higher than that with the smoothest surface.

The flashover voltage \( V_{FO} \) for each roughness can be expressed...
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by using an empirical formula as

\[ V_{\text{FO}} = a \times l^b \ [kV]. \]

Fig. 9. Flashover characteristics as a function of surface roughness (Pyrex®)

Fig. 10. Flashover voltages as a function of insulator length

Fig. 11. Flashover fields as a function of insulator length

increasing insulation strength for a wide range of insulator length.

5.3 Flashover Mechanism The results mentioned in the sections 3 and 5 strongly indicate that the charging of insulator surface leads the bridged vacuum gap to flashover under DC voltage excitation. On the other hand, the reference [17] suggests that mechanical stress is introduced in a thin layer of insulator surface by roughening, and that the stress increases the flashover strength when a pulse voltage is applied. Thus, flashover mechanism of an insulator in vacuum may be different depending on the voltage shape being applied. We need further investigation to discuss these flashover mechanisms.

6. Conclusion

We have examined surface charging and flashover characteristics of a glass insulator under DC excitation in vacuum. The insulator length ranges from 0.3 up to 50 mm, and its surface roughness varies from 0.03 up to 3.1 µm.

As a result, we have confirmed that roughening the insulator surface is effective for a wide range of insulator length in order to;

1. Mitigate the surface charging, and
2. Improve the insulation strength in vacuum.

The surface charging is substantially suppressed at a roughness of \( R_a \geq 3 \) µm. These results are useful not only for high voltage VCB’s but also for other equipment that uses high voltage in vacuum such as particle accelerators.

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References


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