Insulation Characteristics of Bushing Shed at Cryogenic Temperature

W J Kim¹, Y J Kim² and S H Kim¹
¹ Department of Electrical Engineering, Gyeongsang National University and ERI, Jinju, Korea
² Department of Electric Apparatus Testing, Korea Electrotechnology Research Institute, Ansan, Korea

E-mail: shkim@gnu.ac.kr

Abstract. In the development of high-TEM superconducting (HTS) devices, the bushing for HTS devices (HTS bushing) is the core technology, the need to because of supply high voltage to the cable or the winding of the transformer. The lower part of the bushing is exposed to the liquid nitrogen (LN₂), and it has many sheds. In particular, the insulation body with sheds and electrical insulation at cryogenic temperature have attracted a great deal of interest from the viewpoint of the size, weight and efficiency of bushing. This study has mainly investigated the shed and insulation body by comparing glass fiber reinforced plastics (GFRP) in LN₂. We investigated the surface discharge characteristics according to insulating materials, width and height of the shed.

1. Introduction
The HTS power equipment [1-3] is environment-friendly equipment which exceeds the performance limits of conventional equipment in terms of size, weight, and efficiency. The HTS bushing is core technology which must be developed to apply power to the inside of the equipment in order to operate superconducting power machine. However, HTS bushing is now in a development stage around the globe. It is not yet commercially available.

In general, a conductor is wrapped by insulators in bushing [4]. The insulation factors of HTS bushing consist of an upper insulating unit for air surface discharge, thickness for puncture insulation, and a lower insulating unit for surface discharge in LN₂ at the bottom of the flange. In particular, in the lower insulating unit, material technology and insulation technology at cryogenic temperature are essential because of the existence of LN₂ and cryogenic nitrogen gas. Also, there is a high possibility of bubble generation due to heat penetration or quenching. As a result, a decrease in insulation performance is anticipated [5]. Therefore, this study has investigated the electrical and mechanical characteristics of shed materials in LN₂. In addition, the shape, arrangement of shed have been studied.

2. Experimental Apparatus
The insulation materials used for bushing include GFRP, silicon rubber, ethylene propylene rubber (EPDM)/Si, aromatic polyamide (Nomex), and polytetra-fluoro ethylene (Teflon).

Figure 1 (a) and (b) show the electrode system for surface discharge of planar and cylindrical GFRP samples, respectively. As shown in Figure 1(a), the electrode system has used aluminum needle-plane electrode. Surface length(l) is 20, 30 and 40mm, and body diameter(D) is 20, 50, 95 and...
Figure 1. Electrode system for surface discharge; (a) cyrdical GFRP sample with electrodes mounted in the side of the cylinder. (b) planar electrodes mounted on top and bottom of circular GFRP sample.

160mm. As shown in figure 2(b), the aluminum circular electrodes were mounted on the upper (diameter: 46mm) and lower (diameter: 76mm) parts each. In addition, the dependence of width was used with cylindrical GFRP shed 15mm in thickness and 56, 76 and 88mm in diameter. The dependence of height was used with cylindrical GFRP shed 76mm in diameter and 11, 15 and 21mm in thickness. The GFRP samples were designated as two different directions which are the longitudinal (parallel to glass-fiber direction) and lateral direction (cross to glass-fiber direction).

The electrode-installed sample was washed with ethyl alcohol and dried in a drying machine to remove humidity. The electrode-installed sample was fixed to the electrode holder. After arranging the electrode holder in a cryogenic container and filling it with LN$_2$ inside, a high voltage was applied. The high-voltage source was AC (100kV) and the standard impulse (1.2/50μs, 400kV) power supplier. Considering insulation design, impulse breakdown voltage was measured by focusing on the positive impulse voltage with low breakdown voltage.

3. Results and Discussion

Figure 2 shows the characteristics of imp(+) breakdown of various insulating materials under the same conditions. The insulating materials used as planar samples. As shown in this figure, it was the highest in GFRP, followed by in Nomex, Teflon, silicon rubber, and EPDM/Si. Just like the characteristics of AC insulation breakdown, there were good insulation materials with almost no difference except for EPDM/Si and silicon rubber. Also, GFRP was higher than other materials in terms of tensile load, tensile strength, yield stress, and elastic modulus [6]. Therefore, this study has investigated the surface discharge characteristics of GFRP which have superior mechanical and electrical characteristics in LN$_2$.

Figure 2. Imp(+) breakdown characteristics of various insulating materials in LN$_2$. 

Figure 3 shows the surface discharge characteristics according to the lateral and longitudinal directions of cylindrical GFRP. The cylindrical GFRP was 160mm in diameter and 40mm in surface length. Then, AC and imp(+) voltage were applied. As shown in this figure, there is no big difference in voltage. However, the surface discharge voltage in longitudinal direction was slightly higher than that in lateral direction in any cases. In case of HTS bushing, the production in lateral direction is inevitable.

![Surface discharge characteristics according to lateral and longitudinal direction in LN\textsubscript{2} for a cylindrical sample of diameter D and separation l between electrodes (Fig. 1(a)).](image)

**Figure 3.** Surface discharge characteristics according to lateral and longitudinal direction in LN\textsubscript{2} for a cylindrical sample of diameter $D$ and separation $l$ between electrodes (Fig. 1(a)).

Figure 4 shows the surface photograph of cylindrical GFRP sample according to the longitudinal direction after impulse surface flashover.

![Surface photograph of cylindrical GFRP sample according to the longitudinal direction after impulse surface flashover.](image)

**Figure 4.** Surface photograph of cylindrical GFRP sample according to the longitudinal direction after impulse surface flashover.

Figure 4 shows the surface photograph of cylindrical GFRP in a longitudinal direction taken under impulse voltage after surface discharge. In the case of a lateral direction, slightly degraded tracking was observed on the surface. In the case of a longitudinal direction, on the contrary, the discharge path developed in zigzag pattern. The surface discharge voltage of longitudinal direction was higher than that of lateral direction because discharge developed toward glass fiber at a right angle. This study has concentrated on the characteristics of a longitudinal direction.

![Surface discharge characteristics according to surface length in LN\textsubscript{2} for cylindrical sample.](image)

**Figure 5.** Surface discharge characteristics according to surface length in LN\textsubscript{2} for cylindrical sample.
Figure 5 shows the surface discharge characteristics according to surface length when the cylindrical diameter of GFRP was 160mm. As shown in this figure, the surface discharge of AC voltage is lower than that of impulse voltage in GFRP. The equation between impulse voltage ($V_S$) and surface length ($\ell$) is $V_S=4.9\ell^{0.8}$.

Figure 6. Dependence of the surface discharge voltage of a shed as function of (a) width $w$ and (b) height $h$.

Figure 6(a) and (b) show that the dependence of surface discharge voltage on the width and height of GFRP shed. Keeping the height and width of shed at 15mm, the width and height were adjusted. As shown in this figure, despite increase in the width of insulation shed, no dramatic increase in surface discharge voltage occurred. As the height of insulation shed increased, on the contrary, surface discharge voltage increased. It’s been confirmed that increase in the height of insulation shed instead of increase in the width in suppressing the progress of surface discharge. Therefore, when the shed for HTS bushing is designed, it is more effective to increase height of GFRP shed.

4. Conclusion
In terms of insulation materials for superconducting bushing, GFRP—which is superior at cryogenic temperature electrically and mechanically—is desirable. In addition, in terms of surface discharge voltage, longitudinal direction is slightly higher than lateral direction because of the effect of glass ber direction in GFRP. AC surface discharge voltage is lower than impulse voltage in GFRP. The positive impulse voltage ($V_S$)-surface length ($\ell$) equation can be stated as ‘$V_S=4.9\ell^{0.8}$’.

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