Superconductivity and Cryogenics
Vol.13, No.4, (2011), pp.10~13

Electrical characteristics of insulating materials for HTS bushing immersed in LN_2

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Received 24 October 2011; accepted 21 November 2011

Abstract-- **For the operation of high temperature superconducting (HTS) power equipments, it is necessary to develop insulating materials and high voltage (HV) insulation technology at cryogenic temperature of bushing. In this paper, the surface flashover characteristics of various insulating materials in LN_2 are studied. These results are studied at both AC and impulse voltage under a non-uniform field. The negative impulse breakdown voltage of GFRP is slightly higher than the positive impulse breakdown voltage. The use of glass fiber reinforced plastic (GFRP) and polytetrafluoroethylene (PTFE, Teflon) as insulation body for HTS bushing should be much desirable. Especially, GFRP is excellent material not only surface flashover characteristics but also mechanical characteristics at cryogenic temperature. The surface flashover is most serious problem for the shed design in LN_2 and operation of superconducting equipment.**

1. INTRODUCTION

Recently, HTS power equipments such as HTS cable, fault current limiter, transformer and others have attracted much interest from the view point of energy. In order to commercialize HTS power equipments, it is necessary to develop HTS conductor, cooling system, insulation and materials technology and high voltage (HV) bushing. Especially, HV bushing is a very important because it must supply the high voltage to the cable or winding of the transformer. The HV bushing is basically a hollow insulator that allowing a conductor to pass along its center.

Both ends of the conductor in bushing are connected to the winding of machine and supply line. Generally, there are four main parts of the bushing: conductor, insulator with shed, insulation and accessories. For example, the composite HV bushing is made of a conductor wound with GFRP, hollow insulator with GFRP tube and Silicone (Si) rubber housing, insulation, connection clamp and accessories such as flange. And the inner insulation medium is paper which is wound and impregnated with oil.

So far, many papers have been published on the oil, gas and resign insulated bushing and insulation [1-3]. However, there has not been satisfactorily progress in the research and development of HTS HV bushing. This unsatisfactory progress has also made the insulation design of HTS power equipments very difficult.

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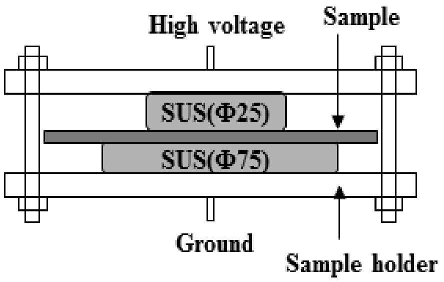
The insulation technology in electrical problems must be solved for the long life, reliability and compact of HTS HV bushing. Until now, we have studied AC breakdown characteristics of 154kV class HTS cable and transformer in LN_2 [4, 5]. However, the study on electrical characteristics of HTS bushing was completely not perfect. Therefore, at first stage, it is important to study the AC and impulse insulation characteristics and various insulating materials for HTS AC bushing.

In this paper, we will discuss mainly on the puncture breakdown and surface discharge characteristics of GFRP, Teflon, EPDM/Silicone alloy compound (EPDM/Si), aromatic polyamide (Nomex) and Si rubber in LN_2. These results are studied at both AC and impulse voltages under a non-uniform field. The use of GFRP and Teflon as the insulating material for HTS bushing should be much desirable. The surface flashover is most serious problem for the shed design in LN_2 and operation of superconducting power equipments.

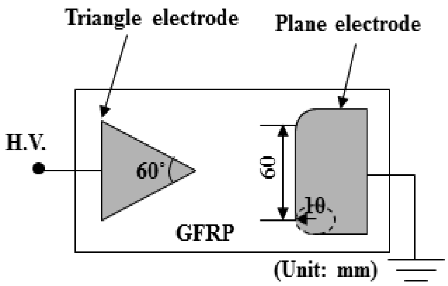
2. EXPERIMENT

Figure 1 shows the electrode system for breakdown and surface discharge, respectively. The electrodes made from stainless steel (SUS) for breakdown test were the plane electrode of upper 25 mmΦ and lower 75 mmΦ. The electrode system is located by the vertical arrangement of SUS electrodes on GFRP plate. The sample of insulating materials was fixed with sample holder. It is almost the same as that of DC [6]. Also, the electrode system for surface discharge is SUS triangle (tip angle: 60 degree) and planar configuration. To avoid the shift of distance in LN_2 between the electrodes, the electrodes were fixed by the polymer bolt on the specimen.

The samples used as solid materials were GFRP, Teflon, Si rubber, EPDM/Si (in 70:30 ratio) and Nomex board, which were 0.5, 1 and 1.5mm in thickness. The surface flashover distance was 5, 10 and 15mm, respectively. Also, the samples used as liquid materials were LN_2. The surface flashover and breakdown voltage is measured at the atmospheric LN_2. The samples with electrodes were dried by using the drier to completely remove the moisture, and cleaned carefully with ethyl alcohol. The sample with electrodes was fixed with sample holder.



(a) Breakdown



(b) Surface flashover discharge

Fig. 1. Electrode system. (a) for breakdown, (b) for surface.

The sample holder was attached to the lower part of bushing of the cryostat made of stainless steel. After introducing the commercial-grade LN_2, voltage was applied between the electrodes of sample. The sample was replaced with new one after each breakdown test. 15 times breakdown and surface flashover voltages were measured. The voltages used are AC and lightning impulse.

3. RESULTS AND DISCUSSION

3.1. Breakdown characteristics

Figure 2 shows GFRP thickness dependence of breakdown voltage under AC and impulse voltage. The breakdown voltage is measured at the atmospheric LN_2. When a negative or positive voltage is applied to the upper electrode (25 mmΦ), we term this "negative impulse" and "positive impulse", respectively. And the error bar shows the maximum, average and minimum value of breakdown voltage, respectively.

As seen in the figure, the AC breakdown voltage of GFRP was lower than the impulse breakdown voltage; it increases with increasing of GFRP thickness. The impulse surface flashover voltage quickly increases with increasing of the GFRP thickness. Also, the impulse breakdown voltage of negative polarity is slightly higher than that of positive polarity. The ratio of negative/positive voltage under impulse voltage is 1.1. For the insulation design of HTS bushing, it is necessary to know the AC and positive impulse voltage of insulating materials in cryogenic environment. From above experiment, the relation between positive impulse breakdown voltage (V_B) and the thickness (l) can be expressed by V_B=71$l^{0.8}$ (kV). It is confirmed that GFRP is excellent insulating material at cryogenic temperature.

The thickness dependence of AC breakdown strength in EPDM/Si, Teflon, Nomex and Si rubber is shown in Figure 3 with in comparison those of GFRP. As is evident from this figure, the AC breakdown characteristic of Si rubber is lower than that of GFRP.

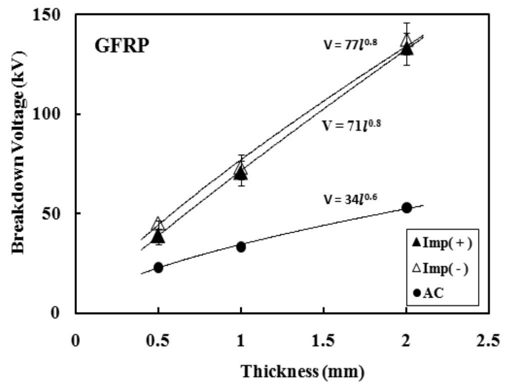


Fig. 2. GFRP thickness dependence of breakdown voltage under AC and impulse voltage.

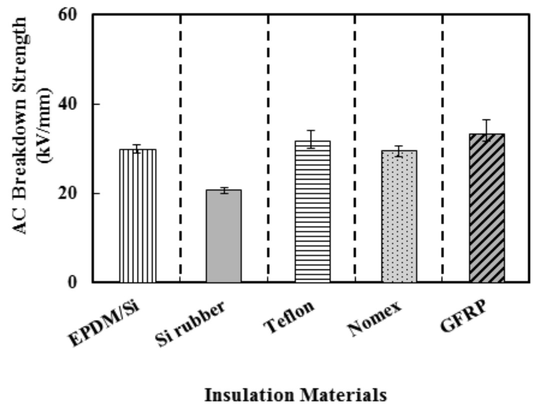


Fig. 3. Breakdown characteristics of various insulating materials under AC.

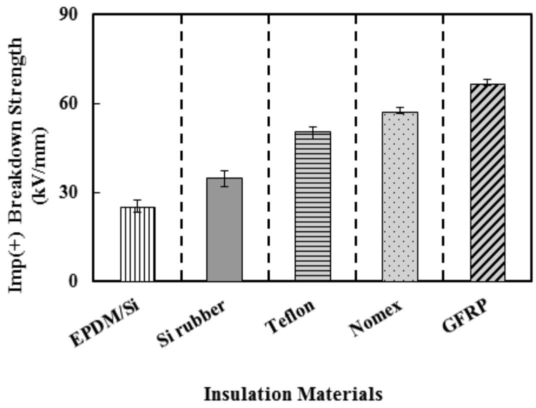


Fig. 4. Breakdown characteristics of various insulators under positive impulse.

However, the AC breakdown characteristics of EPDM/Si, Teflon and Nomex seem to be similar to that of GFRP. It is confirmed that EPDM/Si, Teflon, GFRP and Nomex are excellent insulating materials for HTS AC bushing.

Figure 4 shows the thickness dependence of positive impulse breakdown strength. As is evident from this figure, the positive impulse breakdown strength is higher in the order GFRP, Nomex, Teflon, Si rubber, EPDM/Si. Especially, the impulse breakdown strength of Si rubber, EPDM/Si is low remarkably. The surface of EPDM/Si and Si rubber is observed the cracks, breakdown hole, and broken parts after breakdown.

3.2. Surface discharge characteristics

Figure 5 shows the flashover length dependence of surface flashover voltage of GFRP under AC and impulse voltage. As seen in the figure, the AC surface flashover voltage of GFRP was lower than the impulse surface flashover voltage; it increases with increasing of electrode length. The impulse surface flashover voltage quickly increases with increasing of the electrode length. Also, the impulse surface flashover voltage of negative polarity is slightly higher than that of positive polarity. The ratio of negative/positive voltage is approximately 1.1. From above experiment, the relation between positive surface flashover voltage (V_S) and the electrode length (l) can be expressed by V_B=13$l^{0.6}$ (kV).

On the other hand, the flashover length dependence of AC surface flashover voltage in LN_2 is shown in Figure 6 with in comparison those of GFRP, EPDM/Si, Teflon, GFRP, Nomex and Si rubber. As seen in the figure, the AC surface flashover voltage is higher in the order EPDM/Si, Teflon, GFRP, Nomex, Si rubber in every flashover length. However, it is in the range of error. The characteristics of AC surface flashover seem to be similar in all the samples. Therefore, it is confirmed that EPDM/Si, Teflon, GFRP, Nomex and Si rubber are excellent insulators for HTS transformer bushing.

Figure 7 shows the electrode length dependence of positive impulse surface flashover voltage. As evident from this figure, the positive impulse surface flashover voltage is higher in the order Nomex, EPDM/Si, Teflon, GFRP, Nomex and Si rubber in every electrode length. It seems to be almost the same because it is in the range of error. However, the impulse surface flashover voltage of Nomex is high remarkably. The surface of EPDM/Si, Si rubber is observed the crack or broken parts after surface flashover.

Figure 8 shows the photographs of material surfaces obtained by using the camera after many breakdown or flashover events under impulse voltage. A damage of surface can be observed by the eyes. As evident from Fig. 8 (a), the surface of GFRP is observed a discharge traces.

It is not severely degraded by the surface discharge. It becomes more severe with the increase of applied voltage. Especially, in the case of impulse, the degradation of surface becomes more severe. It can be interpreted in terms of the discharge energy. Also, such phenomena at cryogenic temperature were observed with Teflon (Figure 8(b)). However, in the case of Nomex (Figure 8(c)), the surface becomes degraded severely according to break the molecular chain. Therefore, the use of Nomex as the insulating materials for HTS bushing should not be desirable. On the other hand, the surface of EPDM/Si (Figure 8(d)) and Si rubber (Figure 8(e)) are severely damaged with the cracks, broken parts after breakdown or surface flashover.

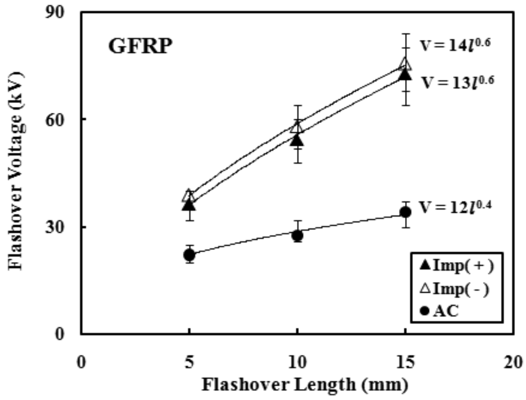


Fig. 5. Surface flashover characteristics of GFRP.

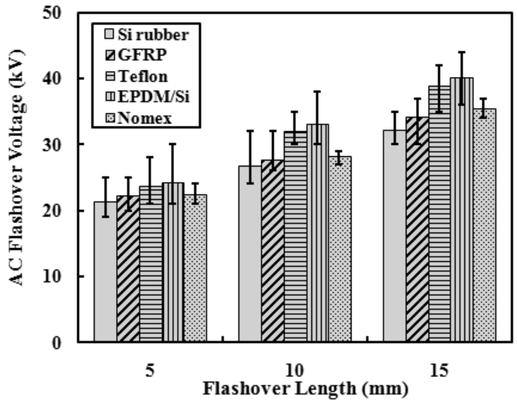


Fig. 6. Surface flashover characteristics of various insulating materials under AC.

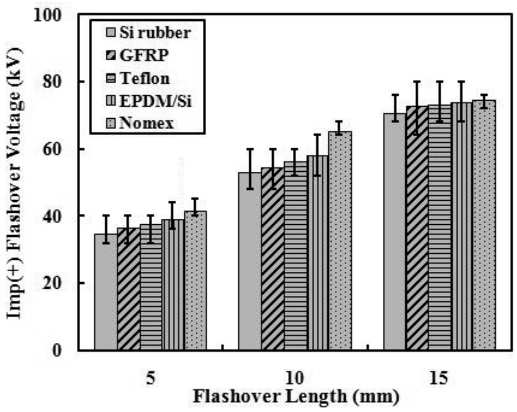
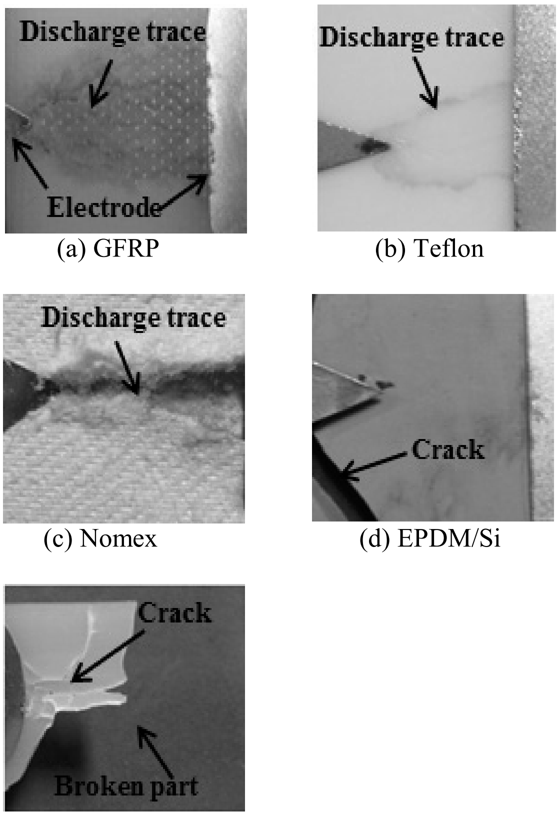


Fig. 7. Surface flashover characteristics of various insulating materials under positive impulse.



(a) GFRP (b) Teflon

(c) Nomex (d) EPDM/Si

(e) Si rubber

Fig. 8. Photographs of material surfaces after surface discharge. (a) GFRP, (b) Teflon, (c) Nomex, (d) EPDM/Si and (e) Si rubber.

It can be interpreted in terms of the glass transition temperature (T_g) of materials [7]. It is clear from these results that at cryogenic temperature EPDM/Si and Si rubber cannot be used the insulating material for HTS bushing.

In conclusion, the surface flashover strength (2-4 kV/mm) of GFRP in LN_2 is much lower than that of breakdown strength solid insulating materials such as GFRP and others. It indicates that the surface flashover is most serious problem for the shed design in LN_2 and operation of superconducting power equipments. Also, the use of GFRP and Teflon as the insulation body for HTS bushing should be much desirable. A more detailed study on other insulating materials for HTS bushing is now progress.

4. CONCLUSION

We have studied mainly on the breakdown and surface discharge characteristics of insulating materials under AC and impulse voltage were studied. The results may be summarized as follows:

(1) The negative impulse breakdown voltage of GFRP is slightly higher than the positive impulse breakdown voltage. The ratio of negative/positive voltage under impulse voltage is 1.1.

(2) AC breakdown characteristics of EPDM/Si, Teflon and Nomex seem to be similar to that of GFRP. It is confirmed that EPDM/Si, Teflon, GFRP and Nomex are excellent insulating materials for HTS AC bushing.

(3) The impulse breakdown strength of GFRP, Nomex and Teflon seems to be almost the same because it is in the range of error. Especially, the impulse breakdown strength of Si rubber, EPDM/Si is low remarkably.

(4) The surface of GFRP and Teflon are not severely degraded by the surface discharge. Especially, the surface of Si rubber and EPDM/Si are severely damaged with the cracks or broken parts after breakdown or surface flashover. In conclusion, the use of GFRP and Teflon as insulation body for HTS bushing should be much desirable.

(5) The surface flashover strength (2-4 kV/mm) of GFRP in LN_2 is much lower than that of breakdown strength solid insulating materials such as GFRP and others. The surface flashover is most serious problem for the shed design in LN_2 and operation of superconducting equipments.

ACKNOWLEDGMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2011-0013667).

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