Superconductivity and Cryogenics
Vol.14, No.4, (2012), pp.20~23
http://dx.doi.org/10.9714/sac.2012.14.4.020

An Investigation on Surface Flashover Characteristics of FRP in Several Insulation Gases for the Spacer of Cryogenic Bushing

Jae-Sang Hwang, Woo-Ju Shin, Jae-Kyu Seong, Jong-Geon Lee and Bang-Wook Lee

Hanyang University

Received 12 October 2012; accepted 12 November 2012

Abstract—**Superconducting equipment has been actively investigated for securing the environment and energy technology (ET) in various parts of the world. Despite these movements, a high voltage cryogenic bushing, which plays an important role of interconnection between the electric power systems and superconducting devices, has not been fully developed due to severe insulation requirements. A gas insulated cryogenic bushing has been investigated as one of our projects since 2010. As a basic step to obtain the design parameters for cryogenic bushing, we focused on the surface flashover characteristics of glass fiber reinforced plastic (FRP) in several insulation gases. For the surface flashover tests, several insulation gases including SF_6, CF_4 and N_2 gas were prepared. Various length of FRP specimens were fabricated in order to obtain the fundamental data for creepage distance of FRP. The first specimen group was from 2 mm to 10 mm with 2 mm intervals and the second specimen group was from 20 mm to 100 mm with 20 mm intervals. And the gas pressure was varied from 1 bar to 4 bar. An AC overvoltage test and a lightning impulse test were performed. Then the experimental results of surface flashover were obtained and analyzed. Based on these results, it would be possible to design the optimum creepage distance of FRP in a cryogenic bushing.**

Keywords: **CF_4, Creepage distance, Cryogenic bushing, FRP, N_2, SF_6, Spacer, Surface flashover.**

1. INTRODUCTION

At the beginning of 21st century, many researchers involved in the research and development of superconducting equipment have anticipated that the commercialization of superconducting devices would be come true in the near future. But, up to now, only a few superconducting devices have been on field trial for real electric power systems. In order to speed up the commercialization of superconducting devices, some unsolved matters of cryogenic dielectric issues should be settled [1, 2].

Especially for the interconnection of superconducting equipment with conventional electric power systems, the essential components are cryogenic bushings. However, the cryogenic bushings have not been fully developed due to severe insulation requirements. Cryogenic bushings should be safely able to supply the current and overcome high voltage cryogenic issues under intense thermal variation from room temperature to extremely low temperature [3].

Due to this steep temperature differences, conventional SF_6 gas bushing or oil impregnated porcelain bushing could not be directly applicable because of liquefaction of SF_6 gas or freezing of oil in cryogenic environment. These liquefaction phenomena of SF_6 gas and freezing of oil are detrimental to dielectric performance of high voltage bushings. Therefore, the cryogenic bushings which are operated in cryogenic environment are always exposed to the danger of reduction of the dielectric performance [4].

In order to solve these critical problems, the gas insulated part of cryogenic bushings should be blocked from cryogenic environment caused by liquid nitrogen. Therefore, a newly developed spacer is needed to maintain the current lead. By changing the material of the spacer, the penetration of an extremely low temperature could be minimized. As a material of the spacer, a glass fiber reinforced plastic (FRP) was chosen due to its outstanding electrical and mechanical properties, as well as its endurance to thermal contraction and expansion.

As a fundamental step to obtain the design parameters of the FRP spacer for cryogenic bushing, we focused on the surface flashover characteristics of FRP in several insulation gases. For the surface flashover tests, several insulation gases including SF_6, CF_4 and N_2 gas were prepared. In order to determine the dielectric performance of FRP specimens, AC overvoltage tests and lightning impulse tests were performed. Based on these investigations, it would be possible to design the optimum creepage distance of FRP spacer in gaseous media for the cryogenic bushing.

2. THE STRUCTURE OF CRYOGENIC BUSHING

2.1. Three Insulation Parts of Cryogenic Bushing

According to insulation gases parts of the bushing, it could divide into three parts as shown in Fig. 1. First, the upper part of the bushing which is the most far from the liquid nitrogen was filled with SF_6 gas at pressures up to 3 bar. This part could be easily insulated because the dielectric properties of SF_6 gas have been reported in many ways and it operates at room temperature.

Second, the middle part of the bushing which is located

* Corresponding author: bangwook@hanyang.ac.kr

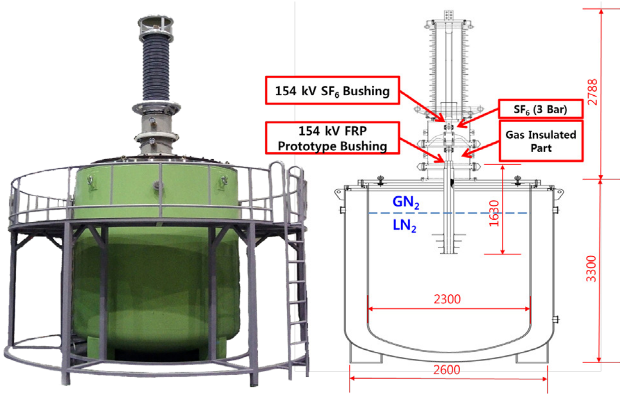

Fig. 1. Cryogenic bushing installed on big cryostat.

Fig. 2. FRP spacer.

between the upper part and the lower part is relatively more difficult to insulate than the upper part therefore it should be filled with suitable gas considering the temperature gradient.

Finally, the lower part should be filled with pressurized N_2 gas because when N_2 gas is applied there is no liquefaction and the breakdown strength was maintained over the time in the cryogenic environment.

2.2. FRP Spacer for the Middle Part

As a material of the spacer for conventional bushing, epoxy has been widely used due to its outstanding dielectric performance, but it is hard for the material to be directly applicable to an extremely low temperature environment. The epoxy material could not withstand the steep thermal variation. Therefore, the material of the spacer for cryogenic bushing should be chosen another one which could settle the brittle and fragile nature in the cryogenic environment.

For a solution of the material selection, FRP was chosen due to its outstanding electrical and mechanical properties, as well as its endurance to thermal contraction and expansion in the cryogenic environment. Fig. 2 shows the manufactured FRP spacer which is installed in the middle part of cryogenic bushing.

3. EXPERIMENTAL SET-UP

Fig. 3 shows the block diagram of breakdown test. The experimental set up was comprised of an AC overvoltage transformer (HIGHVOLT™: 400 kVA) for the AC overvoltage tests, an impulse high voltage generator (HIGHVOLT™: 1.6 MVA) for the lightning impulse tests, a voltage capacitive divider. Using up and down method, the standard lightning impulse voltage of 1.2/50 μs which have both positive and negative polarities was applied to the experimental test cell. Between the tests, 10 minutes time interval was given for the stabilization of gases. The test conditions were t=21°C, h=11.08 g/m^3 and b=1016 mbar which are almost corresponded to the standard reference atmosphere (t_0=20°C, h_0=11 g/m^3 and b_0=1013 mbar) in IEC 60060-1. And an experimental test cell and a cylindrical FRP specimen were shown in the right side of Fig. 3.

TABLE I
CHARACTERISTICS OF ELECTRICAL INSULATION GASES.

Gas	Molar Mass (g/mol)	Melting Point (K)	Boiling Point (K)	Density (kg/m^3)
SF_6	146.06	222.2	209	6.27
CF_4	88.0043	90	145	3.72
N_2	28.02	63.15	77.36	1.185

For the surface flashover tests, several insulation gases including SF_6, CF_4 and N_2 gas were prepared and their material properties were listed in Table I. In order to evaluate the surface breakdown characteristics, the cylindrical FRP specimens were fabricated in two ways in order to obtain the trend line in overall viewpoint. The first specimen group was from 2 mm to 10 mm with 2 mm intervals and the second specimen group was from 20 mm to 100 mm with 20 mm intervals. To measure the creepage distance of FRP in certain insulation gas, the trend line should be calculated using at least ten points of surface breakdown voltage values.

In case of the gas pressure, it was selected from 1 bar to 4 bar in order to determine the optimal gas pressure.

The FRP test specimen was fixed between two plane copper electrodes and the length of GFRP specimen was altered according the results of surface flashover tests. The height and width of gas chamber is 670 and 180 mm respectively.

4. RESULTS AND DISCUSSION

In order to evaluate the dielectric performance of FRP specimens and determine the creepage distance of that for the FRP spacer in the middle part of cryogenic bushing, AC overvoltage tests and lightning impulse tests were performed and analyzed.

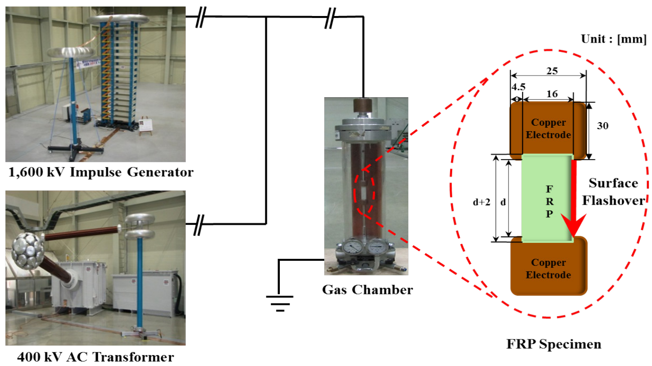

Fig. 3. Block diagram of experimental set-up and the dimension of the FRP specimen.

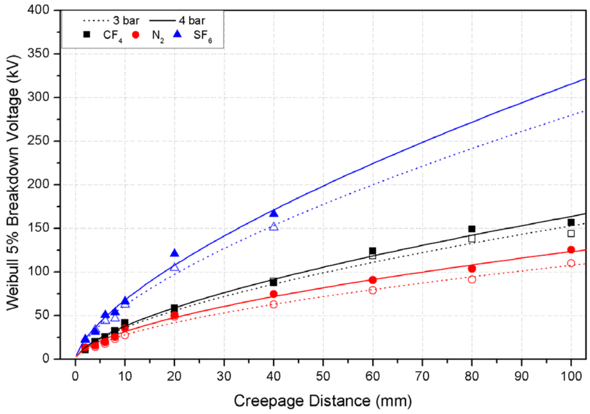

Fig. 4. Surface flashover test results of FRP in different gases for AC overvoltage test.

When the distance of the FRP specimen was larger than 40 mm, it was impossible to measure the breakdown voltage of SF_6 gas when AC overvoltage and lightning impulse with both polarities were applied, because breakdown voltage of SF_6 was much superior to the flashover clearance of the gas chamber.

Fig. 4 shows the comparison of the Weibull 5% probability distribution plot of surface flashover test of FRP specimens when AC overvoltage and both polarities lightning impulse were applied. According to the increase of creepage distance, the breakdown voltage has been increased linearly.

In all gas pressures, the surface breakdown of SF_6 gas was the highest among other gases. Calculating the electrical breakdown voltage between SF_6, CF_4, and N_2 at 3 bar, CF_4 has 55% of breakdown voltage and N_2 has 45% of breakdown voltage compared to that of SF_6.

Fig. 5 and Fig. 6 represent the comparison of the Weibull probability distribution plot of surface flashover test of FRP in gaseous media when positive and negative impulse voltage was applied. Once again, SF_6 gas has shown the highest dielectric performance regardless of polarity effect in all gas pressures. Comparing the positive and negative impulse voltage test results, the electrical breakdown voltage was higher at the negative impulse test than at the positive one. When negative corona occurs, the

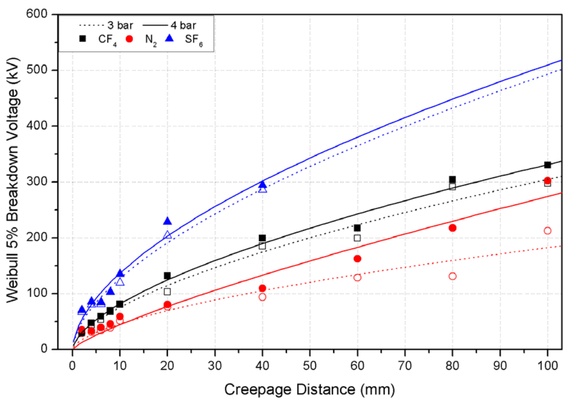

Fig. 5. Surface flashover test results of FRP in different gases for positive lightning impulse test.

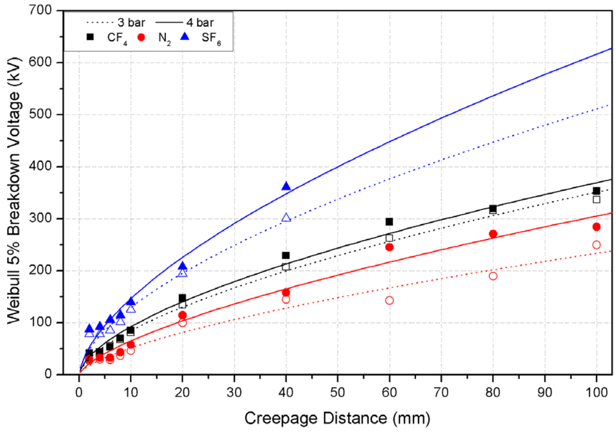

Fig. 6. Surface flashover test results of FRP in different gases for negative lightning impulse test.

corona stabilization is caused by Trichel pulses. The electric field near the cathode electrode is enhanced but the region to ionize is decreased.

By these reasons, ionization process stops and then the ionization start repeatedly. This phenomenon is the cause of Trichel pulses [5]. Therefore, the negative polarity breakdown voltage is higher than positive polarity one.

For this reason, as the basis of impulse design parameter, the negative impulse test results were adopted due to higher breakdown strength compared to the positive one.

Comparing the electrical breakdown voltage both at 3 bar and 4 bar gas pressure, the breakdown strength of SF_6 is almost two times higher than that of CF_4. When N_2 was used as insulation gases, its surface breakdown voltage was just one third of SF_6. From Fig. 5, it was clearly shown that N_2 was not appropriate for the insulation of gaseous space in the middle part of cryogenic bushing.

In case of CF_4, it is essential to increase the gas pressure more than SF_6 to acquire reliable breakdown voltage. As a compromised measure, the mixture of SF_6 and CF_4 could be the viable option for obtaining sufficient creepage distance in cryogenic bushing.

Considering the optimum pressure of insulation gases among both 3 bar and 4 bar, the breakdown voltage results at 4 bar was naturally higher than that at 3 bar. But instead of selecting 4 bar, 3 bar is reasonable for the thickness of cryostat layer and the prevention of leakage problems.

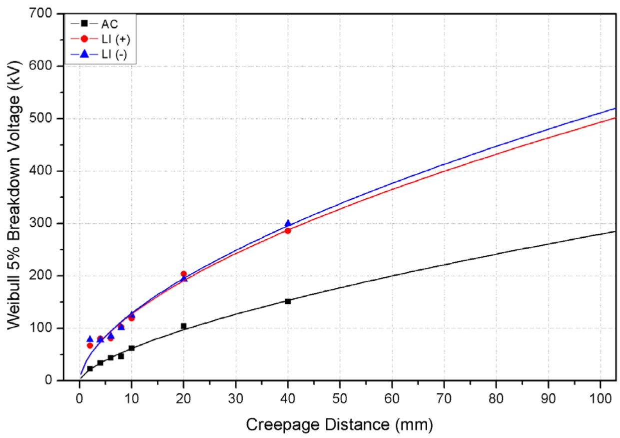

Fig. 7. Surface flashover test results of FRP in SF_6 gas.

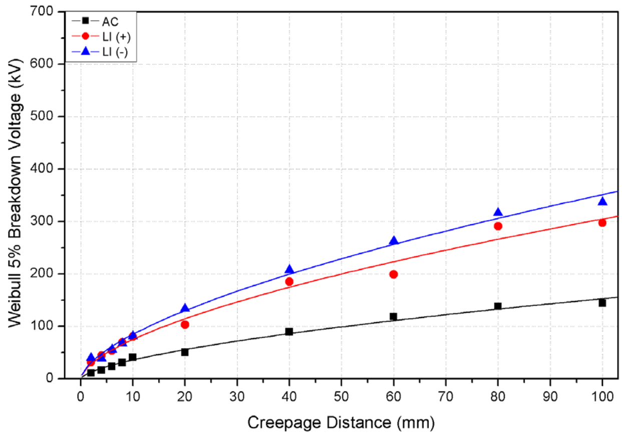

Fig. 8. Surface flashover test results of FRP in CF_4 gas.

Therefore, 3 bar pressure was taken as a nominal gas pressure of FRP in gaseous media. Trend line equations of each gas at 3 bar have been calculated by power type trend lines which were drawn by negative lightning impulse breakdown voltage value as shown in Table II.

The creepage distances of the FRP spacer in several insulation gases for cryogenic bushing have been proposed by substituting 650 kV BIL (IEC standard for 154 kV bushing) into trend line equation. In trend line equation in Table II, x is the creepage distance and y is the breakdown voltage value.

Consequently, when SF_6 gas is applied it was finally decided to design a 150 mm creepage distance for the FRP spacer for 154 kV extra high voltage cryogenic bushing. If the creepage distance of FRP in SF_6 was adopted as a criterion, the creepage distance of FRP in CF_4 should be increased 180% more than that of SF_6. When N_2 was used, the creepage distance in gaseous media should be increased 317% more than that of SF_6.

The creepage distance of the FRP in SF_6 was required the shortest distance, but considering the liquefaction of SF_6 due to steep temperature gradient in cryogenic environment, the pressure increase of CF_4 or the usage of mixture of CF_4 and SF_6 is preferable to get the reliable breakdown characteristics against surface flashover in gaseous media.

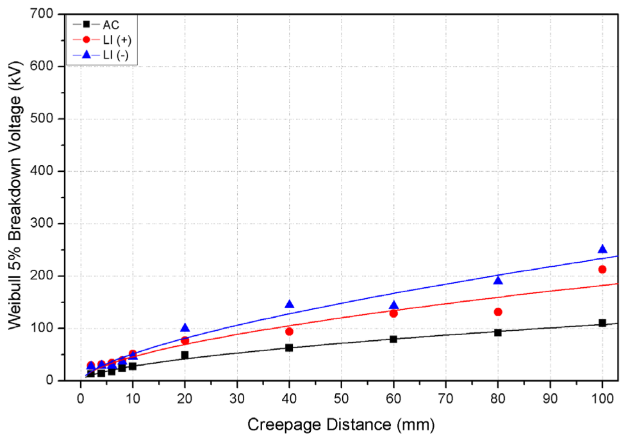

Fig. 9. Surface flashover test results of FRP in N_2 gas.

TABLE II
TREND LINE EQUATIONS AND CREEPAGE DISTANCES CALCULATED BY NEGATIVE LIGHTNING IMPULSE TESTS.

Gas	Pressure	Trend Line Equation	Creepage Distance
SF_6	3 bar	$y = 32.606x^{0.5977}$	150 mm
CF_4	3 bar	$y = 20.482x^{0.6172}$	270 mm
N_2	3 bar	$y = 11.427x^{0.6555}$	475 mm

5. CONCLUSION

Surface flashover characteristics of FRP in gas insulated circumstances were obtained from lightning impulse voltage tests and AC overvoltage tests. The relations between gas pressure of SF_6, CF_4 and N_2 with different creepage distance were analyzed. From the test results, it was possible to deduce following results. First, SF_6 gas has shown the highest dielectric performance in all voltage sources. Second, considering the optimum pressure of insulation gases, 3 bar is reasonable for the thickness of cryostat layer and the prevention of leakage problems. Finally, the creepage distances of the FRP spacer in several insulation gases have been estimated. Consequently, the creepage distance of the FRP in SF_6 was required the shortest distance, but considering the liquefaction of SF_6 due to steep temperature gradient in cryogenic environment, the pressure increase of CF_4 or the usage of mixture of CF_4 and SF_6 is preferable to get the reliable breakdown characteristics against surface flashover in gaseous media.

ACKNOWLEDGMENT

This work has been supported by KESRI (20101020300610), which is funded by MKE (Ministry of Knowledge Economy).

REFERENCES

[1] W. J. Shin, J. K. Seong, J. S. Hwang, B. W. Lee, "Evaluation of Uniform and Non-uniform Breakdown Characteristics of Liquid Nitrogen with Different Electrode Materials", *IEEE Trans. Appl. Supercond*. Vol. 22, No. 3, pp. 7701404, June 2012.

[2] Liye Xiao and Liangzhen Lin, "Recent Progress of Power Application of Superconductor in China", *IEEE Trans. Appl. Supercond.*, Vol. 17, No. 2, pp. 2355-2360, June 2007.

[3] J. S. Hwang, W. J. Shin, J. K. Seong, T. G. Park, S. H. Lee, B. W. Lee, "Experimental Design and Test of 100 kV Extra High Voltage Prototype Bushing with CF_4 as Insulation Gas for Superconducting Equipment", *IEEE Trans. Appl. Supercond*. Vol. 22, No. 3, p. 7701204, June 2012.

[4] S. H. Lee, W. J. Shin, Umer. A. Khan, S. H. Oh, J. K. Seong and B. W. Lee, "Design and installation of extra high voltage crygenic dielectric test facilities for the superconducting electric equipment", *Physica C: Superconductivity and Its Applications* Vol. 471, Issues 21–22, pp. 1576-1580 Nov. 2011.

[5] P. Sattari, C. F. Gallo, G. S. P. Castle and K. Adamiak, "Trichel Pulse Characteristics-Negative Corona Discharge in Air", *Journal of Physics D: Applied Physics*, Vol. 44, No. 15, April 2011.