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Analysis on the dielectric characteristics of a composite insulation system composed of LN_2 and GN_2

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Abstract

A liquid nitrogen (LN_2) is usually used to be a coolant and insulant for a HTS coil system. HTS wires for a superconducting apparatus may be surrounded by gaseous nitrogen (GN_2) due to film boiling generated by a quench or voids occurred by electrical breakdown. The increased maximum electric field intensity at GN_2 may result in the degradation of dielectric strength of a HTS coil system. In this paper, a study on the dielectric characteristics of a composite insulation system composed of LN_2 and GN_2 is performed. A sphere-to-plane electrode system made with stainless steel is used to perform the experiments under AC and lightning impulse voltage condition. A sphere electrode is surrounded by GN_2 and a plane electrode is immersed into LN_2 to conduct dielectric experiments with a composite insulation system. The dielectric experiments are performed according to the level of LN_2 from the plane electrode to a sphere electrode. It is found that the dielectric characteristics of a composite insulation system are dependent on the level of LN_2 and the field utilization factor of an electrode system.

Keywords: composite insulation, high voltage, nitrogen, superconducting

1. INTRODUCTION

A liquid nitrogen (LN_2) has been widely used to develop a high voltage superconducting apparatus due to excellent electrical characteristics and lower costs compared with other cryogenic coolants such as liquid helium. However, HTS wires may be surrounded by gaseous nitrogen (GN_2) in a quench state because LN_2 is evaporated during a quench. The electrical reliability in a composite insulation system composed of LN_2 and GN_2 is worse than that in full LN_2 at a dielectric system. The increased electric field intensity at a gaseous layer may result in the degradation of dielectric strength. In this paper, a study on the dielectric characteristics of a composite insulation system composed of LN_2 and GN_2 is performed. A sphere-to-plane electrode system made with stainless steel is used in the experiments under AC and lightning impulse voltage condition. The high voltage is applied to a sphere electrode and a plane electrode is grounded. The gap of a sphere-to-plane electrode is set at 4mm to simulate a dielectric system such as turn-to-turn, turn-to-enclosure, current lead-to-cooling plate, and so on. The condition of composite insulation system is controlled by adjusting the level of LN_2 between a sphere-to-plane electrode.

2. EXPERIMENT

2.1. Experimental Set-up

High voltage is applied to an electrode system by using an AC (60Hz) power supply with a maximum capacity of 100kV, and a lightning impulse (1.2/50μs) power supply with a maximum capacity of 600kV. The experiments are repeated ten times for every condition and, eight values, except for the extrema were used to calculate the experimental results at sparkover. A time interval of experiments is set at 10 min in order to minimize the influence of voids and a space charge generated by sparkover [1]. Also, the ramping rate of AC voltage is set at 1kV/s. A schematic drawing of dielectric experiments is shown in Fig. 1. A sphere-to-plane electrode system was set in the cryostat, and GN_2 was injected after vacuuming. The level of LN_2 is measured by the PT-100 sensor and the 218 temperature monitor of LakeShore. The level of LN_2 between a sphere and plane electrode was set as shown in Fig. 2. The specifications of an electrode system is shown in Table. 1. Several kinds of sphere electrode systems with various diameters were used to conduct dielectric experiments.

2.2. Experimental Results

In this study, electrical breakdown characteristics of a composite insulation system with respect to the level of LN_2 were examined under AC and lightning impulse voltage at a absolute pressure of 1bar. The experimental results are analyzed by the Weibull distribution to calculate 0.1% probability of electrical breakdown ($V_{BD,0.1\%}$). Fig. 3 shows $V_{BD,0.1\%}$ of a composite insulation system with respect to the level of LN_2 and various sphere electrode

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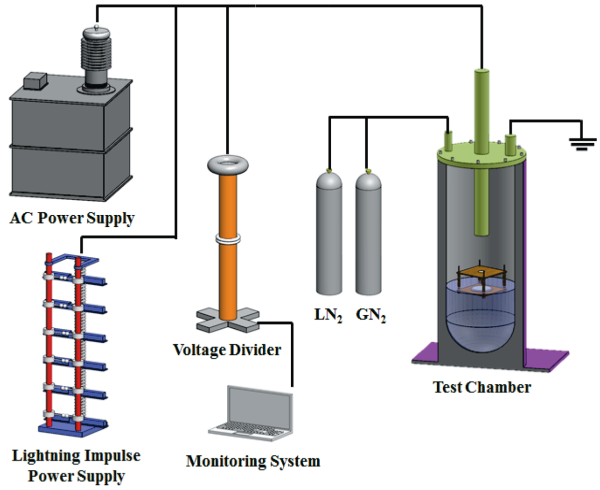
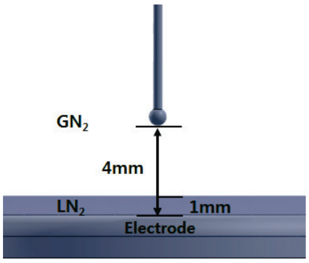


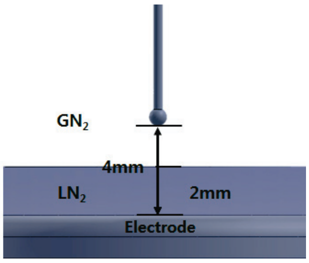
Fig. 1. Schematic drawing of a dielectric experiment.

TABLE I
SPECIFICATIONS OF ELECTRODE SYSTEM.

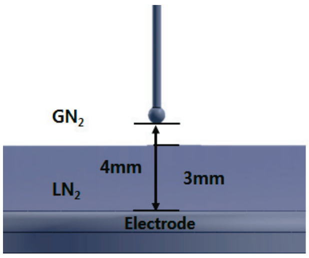
Condition	Specification
Material of Electrode	Stainless Steel 304cd
Sphere Electrode Size [mm]	1, 2, 3, 4, 6
Plane Electrode Size [mm]	Diameter : 120, Thickness : 10 Edge of Radius : 5
Distance of Sphere-to-Plane Electrode [mm]	4
level of LN_2 [mm]	1, 2, 3, LN_2, GN_2



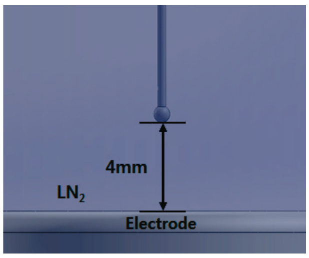
(a) level of LN_2 : 1mm



(b) level of LN_2 : 2mm



(c) level of LN_2 : 3mm



(d) immersed into LN_2

Fig. 2. Schematic drawing of an electrode system with respect to the level of LN_2.

sizes under AC voltage. Fig. 4 shows $V_{BD,0.1\%}$ of a composite insulation system with respect to the level of LN_2 and various sphere electrode sizes under lightning impulse voltage. It was found that $V_{BD,0.1\%}$ is increases by the diameter of a sphere electrode and the level of LN_2 increase. In other words, the GN_2 generated by a quench or the electrical breakdown is critical factor on dielectric strength of a HTS superconducting apparatus.

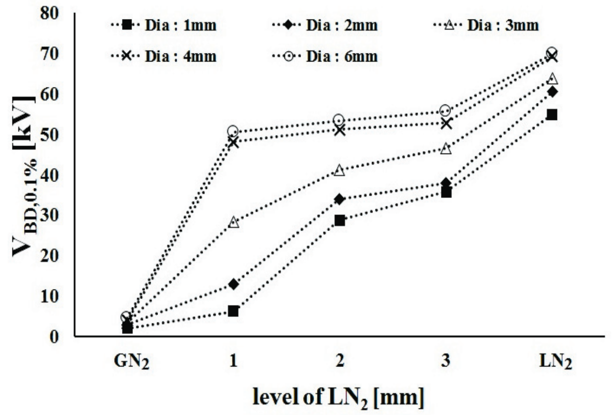


Fig. 3. $V_{BD,0.1\%}$ of a composite insulation system according to the diameter of sphere and the level of LN_2 under AC voltage.

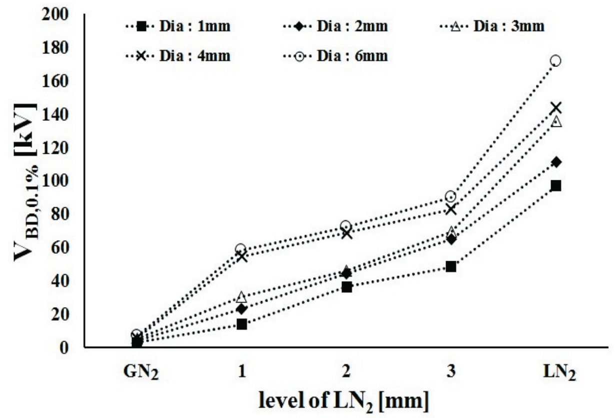
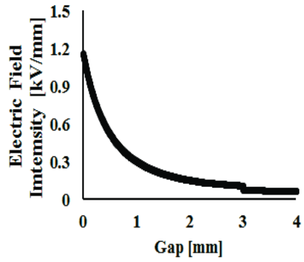
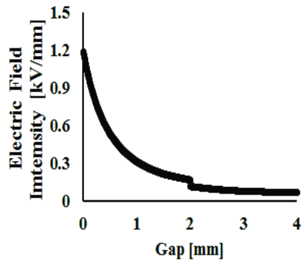


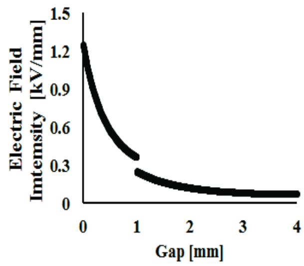
Fig. 4. $V_{BD,0.1\%}$ of a composite insulation system according to the diameter of sphere and the level of LN_2 under lightning impulse voltage.



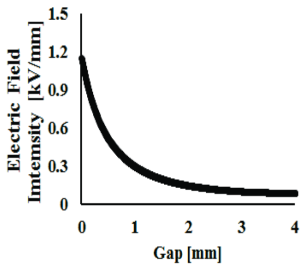
(a) level of LN_2 : 1mm



(b) level of LN_2 : 2mm



(c) level of LN_2 : 3mm



(d) immersed into LN_2

Fig. 5. Distribution of electric field intensity calculated by FEM.

2.3. Electric Field Analysis

The electric field intensity according to the level of LN_2 is calculated by finite element method (FEM). Fig. 5 shows the electric field distribution of an electrode system with various levels of LN_2. In this case, the input voltage is set at 1kV, the diameter of a sphere electrode is set at 2mm, and the level of LN_2 is set at 1, 2, and 3mm.

3. DISCUSSION

In this paper, dielectric experiments on a composite insulation system are performed to verify the dielectric characteristics in a quench state. The dielectric characteristics of a composite insulation system can be explained the by mean electric field intensity at $V_{BD,0.1\%}$ by controlling the level of LN_2. The mean electric fields at under AC and lightning impulse voltage are shown in Fig. 6 and Fig. 7. The $E_{BD,0.1\%}$ indicates the electric field intensity at sparkover voltage with the probability of 0.1%. Also, the Dia. indicates the diameter of sphere electrode. As shown in Fig. 6, the $E_{BD,0.1\%}$ of quasi-uniform field state (diameter of sphere : 4, 6mm) under AC voltage is rarely degraded by the increase of a gaseous layer. In this case, the partial discharge inception voltage can be lowered because the electric field intensity at a gaseous layer is concentrated. The partial discharge inception voltage characteristics of a composite insulation system will be performed in a later paper. The $E_{BD,0.1\%}$ of a non-uniform field state (diameter of sphere : 1, 2, 3mm) under AC voltage decreases rapidly as a gaseous layer increases. Whereas, the $E_{BD,0.1\%}$ under lightning impulse voltage decreases drastically as a gaseous layer increases irregardless of the uniformity of electric field distribution. As shown in Fig. 6 and Fig. 7, the $E_{BD,0.1\%}$ under AC and lightning impulse voltage increases by the diameter of a sphere electrode and the level of LN_2 increases. The aforementioned degree of electric field distribution can be verified by the utilization factors (ξ). The ξ value is a typical parameter which indicates the degree of electrical field distribution, while the field enhancement factor is a reciprocal of the ξ value and means the sharpness and distribution of the electric field. The ξ can be calculated by an FEM [2]. The ξ value can be represented by Eq. (1). The ξ is not dependent on the applied voltage because the E_{MAX} is proportional to the applied voltage. Therefore, the ξ value is determined by the shape and arrangement of an electrode system [3]. The ξ values in this experiment are shown in Table. 2.

The $E_{BD,0.1\%}$ under AC and lightning impulse voltage with respect to the ξ value and the level of LN_2 is shown in Fig. 8 and Fig. 9. As shown in Fig. 8, the $E_{BD,0.1\%}$ of the ξ value between 0.35 and 0.5 under AC voltage is rarely degraded by the increase of a gaseous layer. However, the $E_{BD,0.1\%}$ of the ξ value between 0 and 0.35 under AC voltage decreases rapidly as a gaseous layer increase. Also, Fig. 9 shows that the decrease of the $E_{BD,0.1\%}$ is not related with the ξ value under lightning impulse voltage. It is found that electrode size and GN_2 are critical factor on dielectric strength at quench state.

$$\xi = \frac{E_{MEAN}}{E_{MAX}} \quad (1)$$

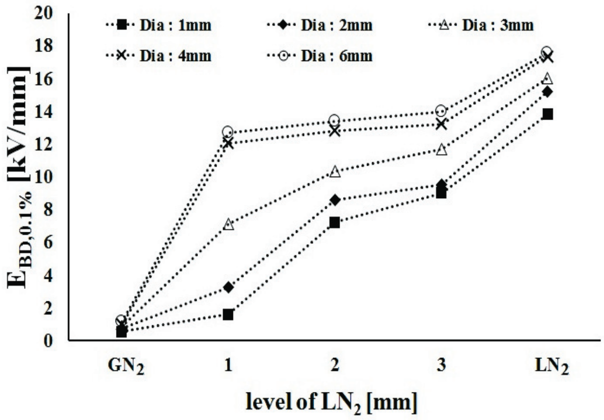


Fig. 6. $E_{BD,0.1\%}$ of a composite insulation system according to the diameter of sphere and the level of LN_2 under AC voltage.

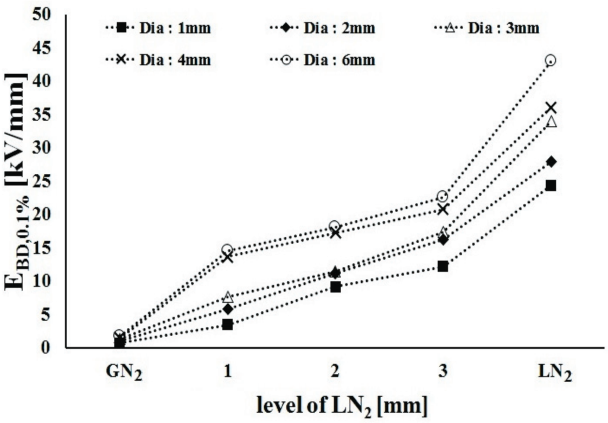


Fig. 7. $E_{BD,0.1\%}$ of a composite insulation system according to the diameter of sphere and the level of LN_2 under lightning impulse voltage.

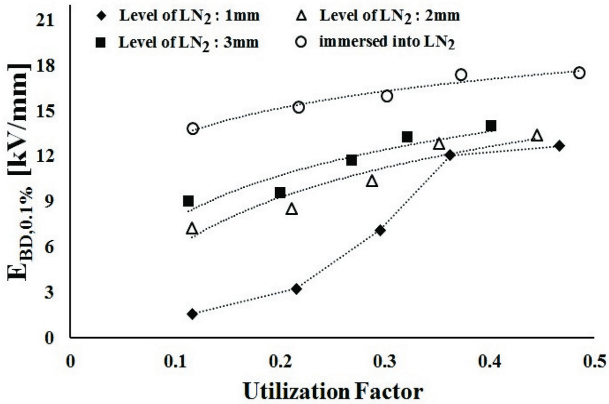


Fig. 8. $E_{BD,0.1\%}$ of a composite insulation system according to the ξ value and the level of LN_2 under AC voltage.

TABLE II
THE CALCULATED FIELD UTILIZATION FACTOR.

level of LN_2 [mm]	Sphere Electrode Size [mm]				
	1 (Emean/Emax)	2 (Emean/Emax)	3 (Emean/Emax)	4 (Emean/Emax)	6 (Emean/Emax)
1	0.11 (0.25/2.15)	0.21 (0.25/1.16)	0.29 (0.25/0.84)	0.36 (0.25/0.69)	0.46 (0.25/0.53)
2	0.11 (0.25/2.17)	0.21 (0.25/1.18)	0.28 (0.25/0.86)	0.35 (0.25/0.71)	0.44 (0.25/0.56)
3	0.11 (0.25/2.23)	0.20 (0.25/1.24)	0.26 (0.25/0.93)	0.32 (0.25/0.77)	0.40 (0.25/0.62)
LN_2	0.11 (0.25/2.14)	0.21 (0.25/1.15)	0.30 (0.25/0.83)	0.37 (0.25/0.67)	0.48 (0.25/0.51)

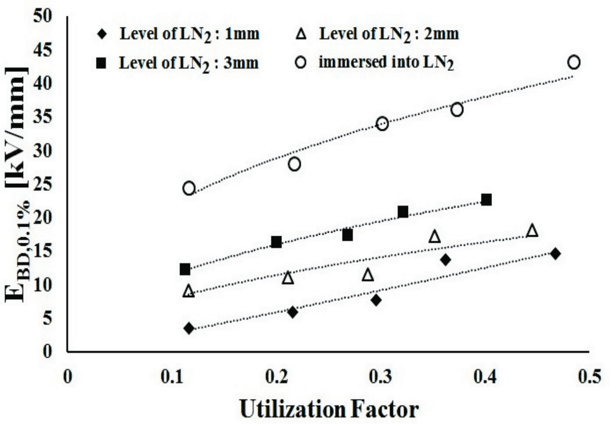


Fig. 9. $E_{BD,0.1\%}$ of a composite insulation system according to the ξ value and the level of LN_2 under lightning impulse voltage.

4. CONCLUSIONS

Dielectric experiments according to the level of LN_2 between a sphere and plane electrode are performed to verify the dielectric characteristics of a composite insulation system. The gap between a sphere and plane electrode is set at 4mm. The dielectric characteristics of a composite insulation system are observed by controlling the level of LN_2. It was found that $E_{BD,0.1\%}$ of quasi-uniform field (diameter of sphere : 4, 6mm) AC voltage is rarely degraded by the increase of a gaseous layer. $E_{BD,0.1\%}$ of a non-uniform field state (diameter of sphere : 1, 2, 3mm) under AC voltage decreases rapidly as a gaseous layer increases. Whereas, the $E_{BD,0.1\%}$ under lightning impulse voltage decreases drastically as a gaseous layer increases irregardless of the uniformity of electric field distribution. In other words, the $E_{BD,0.1\%}$ of the ξ value between 0.35 and 0.5 under AC voltage is rarely degraded by the increase of a gaseous layer. The $E_{BD,0.1\%}$ of the ξ value between 0 and 0.35 under AC voltage decreases rapidly as a gaseous layer increase. Also, the $E_{BD,0.1\%}$ is not related with the ξ value under lightning impulse voltage. Finally the results can be of helped to design a high voltage HTS superconducting apparatus.

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