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Evaluation of Selection Criteria for the Level of Liquid Nitrogen in HTS Magnet System

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Background

- HTS magnet system is immersed in LN_2 and continuously refrigerated by a cryogenic cooling system.
- Especially, in case of the side-wall cooling type, HTS magnet system is located well below the level of LN_2 for thermal and electrical safety and the CGN_2 is filled above LN_2.
- However, the method of determining selection criteria for the optimum level of LN_2 in HTS magnet system has not been yet deeply investigated.
- Therefore, in this work, the process of determining the selection criteria for the level of LN_2 in HTS magnet system is proposed.

Objectives

- A sphere-to-plane electrode system made with stainless steel is used under AC and DC.
- The electric filed intensity according to the level of LN_2 is calculated by the finite element method (FEM) and the experimental results are analyzed using the weibull distribution.
- The utilization factor (ξ) is adopted to analyze the uniformity of the electric filed of the electrode system, and to derive the selection criteria.
- Moreover, a method of selecting the level of LN_2 on the 3D model of HTS magnet is proposed through the calculated selection criteria.

Calculation of selection criteria for the level of LN_2

- $V_{BD,7\%}$ increases as the level of LN_2 and the diameter of the sphere electrode increase as shown Fig. 5.
- Also, the DC voltage do not differ according to the polarity, and the $V_{BD,7\%}$ of the DC voltage is larger than that of the AC voltage.
- ξ is adopted to analyze the uniformity of the electric filed of the electrode system, and to derive the selection criteria as shown equation (1). $\xi = \frac{E_{MAX,1\,kV}}{E_{MEAN,1\,kV}}$ ..... (1)
- The variation of $E_{BD,CGN2,MAX,7\%}$ and $E_{BD,LN2,MEAN,7\%}$ according to ξ considering the level of LN_2 is plotted in Fig. 6, and the equations for calculating $E_{BD,CGN2,MAX,7\%}$ and $E_{BD,LN2,MEAN,7\%}$ are deduced in Table 2.
- It is found that the selection criteria according to the level of LN_2 can be derived.

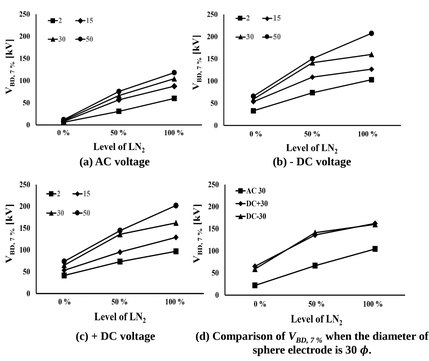

Fig. 5 $V_{BD,7\%}$ according to each voltage

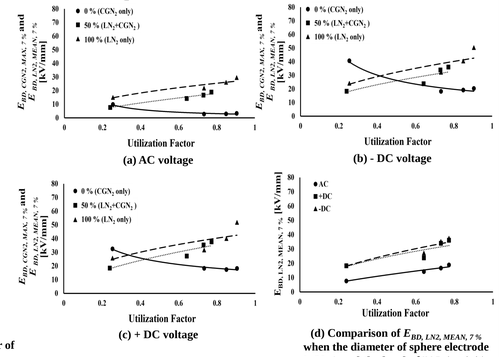

Fig. 6 Comparison of $E_{BD,CGN2,MAX,7\%}$ and $E_{BD,LN2,MEAN,7\%}$ and ξ according to each voltage

Table 2. $E_{BD,7\%}$ according to the level of LN_2 and each voltage

	AC	+DC	-DC
0 %	$y = 2.30x^{-0.53}$	$y = 16.95x^{-0.60}$	$y = 16.38x^{-0.50}$
50 %	$y = 20.81x^{0.71}$	$y = 37.05x^{0.52}$	$y = 40.30x^{0.56}$
100 %	$y = 23.60x^{0.522}$	$y = 44.67x^{0.47}$	$y = 44.29x^{0.42}$

Experimental set-up & analysis method

- Fig. 1 shows the schematic drawing of experimental set-up, and the electrode system is immersed in LN2.
- After degassing the remaining air with a rotary pump, the experiment is performed after waiting for CGN2 to vaporize for 30 min.
- The ramping up rate of voltages is about 1 kV/s., and the time interval is set to 60 sec under AC voltage and 10 min under DC voltage to minimize the influences of space charges.
- Fig. 2 shows the measuring the level of LN_2 between the sphere-to-plane electrodes, and the specifications of experimental conditions are shown in Table 1.
- Each experiment is repeated 7 times on every condition and five values except for maximum and minimum values are used to calculate the mean value of experimental results.
- The experimental results are analyzed by the weibull distribution to calculate 7 % probability for electrical breakdown ($V_{BD,7\%}$) in accordance with IEC 62271-1 as shown Fig. 3.
- The maximum and mean values of electric field intensity ($E_{MAX,1\,kV}$ and $E_{MEAN,1\,kV}$) are calculated through the path of electric field as shown Fig. 4.
- Also, $E_{MAX,1\,kV}$ and $E_{MEAN,1\,kV}$ at $V_{BD,7\%}$ ($E_{BD,CGN2,MAX,7\%}$ and $E_{BD,LN2,MEAN,7\%}$) are calculated because gas insulation is affected by maximum electric field intensity and liquid insulation are affected by the mean electric field.

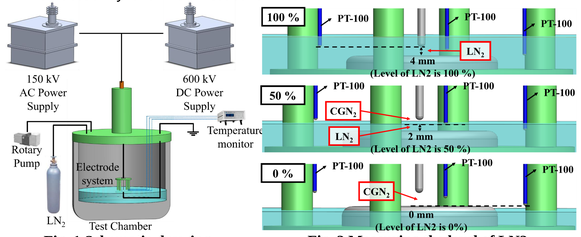

Fig. 2 Measuring the level of LN2 between the sphere-to-plane electrodes

Table 1. Specifications of experimental conditions

Type	Sphere-to-plane
Material	Stainless Steel
Diameter of sphere electrode [mm]	2, 15, 30 ,50
Diameter, thickness and curvature of plane electrode [mm]	100 × 10 × 5
Distance between sphere-to-plane electrodes [mm]	4
Level of LN_2 [mm]	0, 2, 4

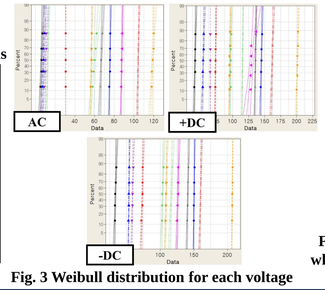

Fig. 3 Weibull distribution for each voltage

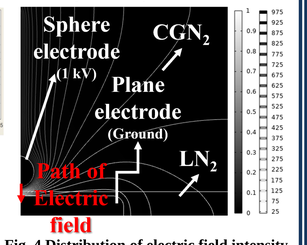

Fig. 4 Distribution of electric field intensity when the diameter of sphere electrode is 30 ϕ and the level of LN_2 is 50 %.

Evaluation method of the level of LN_2 through selection criteria

- Table 3 shows the selection criteria of the level of LN_2 derived through formulas, and as the level of LN_2 increased, it is increased.
- Fig. 7 shows the 3D model on HTS magnet for FEM, and Table 4 shows the parameters for the FEM.
- 100 kV is applied in magnet, and cryostat is grounded, and Fig. 8 shows the electric field distribution of 3D model according to the level of LN_2.
- The Safety Factor (*SF*) is adopted to select the level of LN_2 as shown equation (2), and *SF* is based on 1, where lower means unsafe, and high means safe. $SF = \frac{E_{Selection\ Criteria}}{E_{Designed}}$ ..... (2)
- Fig. 9 shows the $E_{Designed}$ and *SF* of 3D model according to the level of LN_2, and $E_{Designed}$ according to the level of LN_2 increased to 85 %, and then decreased when it reached 100 %.
- Considering the cooling characteristics of the HTS magnet and the selection criteria, 85% is selected with the highest level of LN_2 and SF of 1 or more.

Table 3. Selection criteria of the level of LN_2

	0% (CGN_2)	50% (CGN_2+LN_2)	100% (LN_2)
0 %	2.9	7.7	15.4
50 %	18	18.5	23.4
100 %	19	19	25

Table 4. Parameters for the FEM

Materials	Relative permittivity	Electrical conductivity [S/m]
Magnet	1	$6.00e^{7}$
Cryostat	1	$3.77e^{7}$
Bobbin	4.5	0.004
LN_2	1.45	$2e^{-14}$
CGN_2	1	-

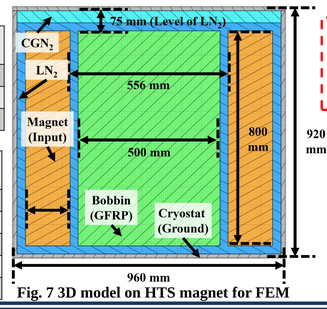

Fig. 7 3D model on HTS magnet for FEM

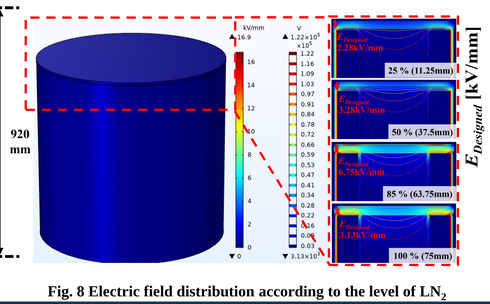

Fig. 8 Electric field distribution according to the level of LN_2

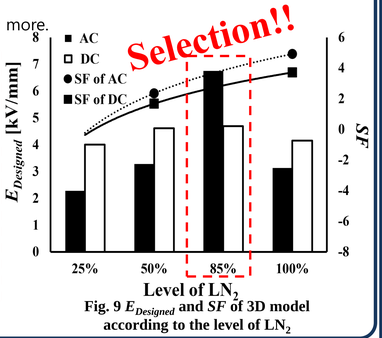

Fig. 9 $E_{Designed}$ and *SF* of 3D model according to the level of LN_2

Conclusion

- In this work, the process of determining the selection criteria for the level of LN_2 in HTS magnet system is proposed.
- Through the proposed selection criteria and evaluation method, it is confirmed that the level of LN2 of the HTS magnet is 85 % most efficient.
- It is found that It is helpful in selecting the level of LN_2 of HTS magnet through the calculated selection criteria and evaluation method.