Effect of a PTFE film on bubble triggered DC breakdown characteristics in liquid nitrogen

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Abstract. In the resistive type DC superconducting fault limiter (R-SFCL), the insulation strength will be decreased seriously when the R-SFCL quenched. Insulation barriers are used inside of the R-SFCL to enhance the electrical breakdown strength of the SFCLs. The objective of this paper is to study the barrier effect on the DC breakdown characteristics of the liquid nitrogen (LN$_2$)/insulation barrier composite system with and without bubbles. In the experiment, the DC breakdown voltage of a pair of rod-plane electrodes with an insulation barrier was measured in the presence of thermal bubbles. The results show that for both the positive and negative polarities, the breakdown voltage of the LN$_2$/insulation barrier composite system is higher than that without the barrier. In the presence of the bubbles, the breakdown voltage of the LN$_2$/insulation barrier composite system is about 1.5 times higher than without the barrier. Furthermore, the breakdown voltage of the LN$_2$/insulation barrier composite system with 0.04 mm PTFE is higher than with 0.1 mm PTFE. The results suggested that the barrier effect could not only improve the insulation strength of the normal state but also the quench state of the R-SFCLs.

Keywords: barrier effect, bubbles, DC breakdown strength, liquid nitrogen, R-SFCL

1. Introduction

High temperature superconducting power apparatus such as high temperature superconducting power cables, superconducting fault current limiters, superconducting magnetic energy storage and so on have been developed in the world [1]. Among them, resistive-type superconducting fault current limiters (R-SFCLs) can not only limit the fault current in the DC side but also limit the fault current limiter in the AC side and the converter station [2]. Furthermore, the R-SFCL with DC fault current breaker was proposed to protect the high voltage DC (HVDC) systems [3-5]. Thus, R-SFCLs is one of the best choices for the HVDC systems. When the R-SFCLs are used in the HVDC system, the insulation structure of it must be designed. Liquid nitrogen (LN$_2$) is not only the cooling medium but also the insulation medium for the R-SFCLs. As it shows in figure 1, when the R-SFCLs connect into the HVDC system, the superconducting tapes are in the high voltage. The dewar is the earth potential. In the normal state, the LN$_2$ protects the superconducting tapes and the dewar from breaking down. However, the R-SFCLs will quench after the fault current occurs. The quenching of the R-SFCLs will bring about the large amount of bubbles.
The bubbles in the LN$_2$ decrease the insulation strength seriously. Even in the normal state, bubbles are also easily formed by even moderate heating in the cryogenic liquids because of a narrow liquid temperature range and low latent heat of vaporization [6]. Thus, it is very important to study the DC breakdown strength of the LN$_2$ with and without bubbles.

![Figure 1. The quenching state of the R-SFCL](image)

The insulation strength of the cryogenic liquid with bubbles have been investigated. Simulated quench conditions and real dynamic quenching conditions were used to investigate the bubble triggered breakdown. Hara [7-10] investigated the DC breakdown characteristic of saturated liquid helium and liquid nitrogen respectively in the presence of simulated quenching conditions under uniform electric fields. The results shown that DC breakdown occurs through locked vapor under simulated bubble conditions. P.Wang [6] studied the bubble motion in liquid nitrogen under non-uniform electric fields. Sauers [11] investigated the effect of bubbles on liquid nitrogen breakdown in plane to plane electrode from 100-250 kPa. He believed the breakdown of the LN$_2$ was due to the formation of a vapor bridge. Okubo and Hayakawa [12, 13] investigated the dynamic breakdown characteristics of liquid helium (LHe) under real dynamic quenching conditions. The bubbles in the liquid helium was induced by superconducting wire and coil. The results revealed that the quench-induced dynamic breakdown of LHe was considered to be triggered by thermal bubbles after quench onset. Some methods were proposed to improve the insulation strength of the R-SFCLs. Hara [14] dealt with electrical forces acting on the thermally induced bubbles in non-uniform field gaps with fins. He suggested that if the fins are formed to guide a bubble from a higher field to a lower one, the thermal bubbles will lesser effect on the breakdown voltage. Hayakawa [15, 16] studied the size effect on breakdown strength in sub-cooled LN$_2$. His results shown that the higher pressures and lower temperature of LN$_2$ can reduce the number the bubbles. Fleszyński [17] firstly proposed the barrier effect to improve the DC insulation strength of superconducting apparatus in DC system. Cheon studied the barrier effect on impulse and AC breakdown voltage [18]. Tanano [19] investigated the effect of the thin insulation film on breakdown phenomena in LN$_2$ in the presence of thermally induced bubble with a cylinder-to-plane electrode when a film was on the surface of the cylinder electrode. His results show that the insulation film has no effect on the breakdown voltage. However, no investigation about the insulation barrier in the middle of the two electrodes effect on the DC breakdown characteristics of liquid nitrogen with bubbles was studied. Thus, the objective of this paper is to obtain the barrier effect on the DC breakdown characteristics in the LN$_2$ with thermally bubbles.

2. Experimental Setup and procedures

Figure 2 shows the schematic diagram of the experimental apparatus. A test sample was put into a cryostat vessel. The cryostat vessel was made of Expanded Polypropylene (EPP). The breakdown voltage in the open bath and in the closed dewar at 0.1 MPa are nearly the same [11]. Considering the safety and economical of the apparatus, the EPP was used as the cryostat vessel which was an open
bath. The size of the cryostat vessel was $500 \times 350 \times 255$ mm. The LN$_2$ poured into the cryostat vessel until the test sample was immersed in the LN$_2$ completely. A DC voltage was applied to the test sample. A heater was put below the test sample which produce the thermal bubbles.

![Experimental Setup](image)

**Figure 2.** Experimental Setup

The details of the test sample are shown in Table 1 and figure 3. The rod-plane electrode are fixed in a platform made of G10. The two electrodes are put horizontal in the cryostat vessel. The distance from the electrode axis to the bottom of the cryostat vessel was $d=75$ mm. Both of the rod and plane electrodes are made of stain stainless steel. The diameter of the rod electrode is 5 mm. The diameter of the plane electrode is 80 mm. The surface treatment for both of the electrodes are 3.2. In the experiment, the gap distance of the rod and plane electrode was 1 mm. The high voltage was applied to the rod electrode. The plane electrode was attached to the ground. The gap distance was adjusted in the room temperature. This can be done in the room temperature because it is found that the shrinkage after cooling down could be ignored. A Polytetrafluoroethylene (PTFE) film was put between the two electrodes. The PTFE film was used as the insulation barrier. It was support by the two insulation boards made of G10. The thickness of the insulation barrier was 0.04 mm. The position of the insulation barrier was nearly in the right middle of the two electrodes. Furthermore, the insulation barrier did not touch both of the electrodes. The heater was used as Kapton heater, as it shown in figure 4.

| Specifications of the test sample |
|----------------------------------|
| **Shape**                        | **Rod** | **Plane** | **Insulation barrier** |
| Diameter $\varphi$ (mm)          | 5       | 80        | 100                   |
| Gap length $b$ (mm)              | 1       |           | /                     |
| Material                         | Stainless steel | PTFE     |
| Surface treatment                | Roughness=3.2 | /         |
| Thickness (mm)                   | -       |           | 0.04 mm               |

As it shows in figure 5 (a), the insulation barrier divides R-SFCLs into two parts. Part I is the superconducting coil and the insulation barrier side. Part II is the insulation barrier and the dewar side. To simulate the quenching state of the R-SFCLs, the bubbles distribution was simulated as figure 5 (b). In figure 5 (b), the insulation barrier also divides the test samples into two parts. Part A is the rod electrode and insulation barrier side. Part B is the insulation barrier and plane electrode side. The heater was put in the Part A side. Thus, bubbles only appear in the Part A side. In figure 5 (b), Part A is to simulate the Part I in figure 5(a). Part B is to simulate the Part II in figure 5(a).
To simulate the bubbles, the Kapton heaters are used to provide heat power. The Kapton heater could be used in the low temperature. The Kapton heaters were located just below the gap of the electrodes. The resistance of a Kapton heater is $20 \, \Omega$. The rate voltage of each Kapton heater is $12 \, V$. Thus, the power of one Kapton heater is about $7 \, W$. In the experiment, three Kapton heaters were attached to the bottom of the cryostat vessel. A stable $12 \, V$ DC power supply was used to control the heat power of the Kapton heaters. The heat power could be adjusted to $0 \, W$, $7 \, W$, $14 \, W$ and $21 \, W$, respectively. In the LN$_2$, the thermal bubbles induced breakdown experiments were done with and without insulation barriers, respectively. The higher the heat power is, the larger amount of the bubbles are.

A DC source of capacity $120 \, kV/5mA$ was connected to the rod-plane electrodes. Both of the positive and negative polarities breakdown voltage were measured. The DC ramp voltage rate was $1kV/s$ until the breakdown happened. For each condition, the experiments were done 12 times.

3. Results and Discussion

3.1. DC breakdown characteristics with insulation barrier

3.1.1. DC breakdown characteristics with different heat power

Figure 6 shows the DC breakdown voltage $V_B$ with and without insulation barrier ($0.04 \, mm$) in the LN$_2$. Figure 6 (a) shows the positive polarity breakdown voltage. Figure 6 (b) shows the negative polarity breakdown voltage. At the same time, the figure 6 also shows the breakdown voltage $V_B$ with different heat power.
Figure 6. Comparison of DC breakdown voltage with or without barrier under different heat power.

Figure 6 shows that when the heat power increase, the breakdown voltage of both the LN$_2$ and LN$_2$/insulation barrier composite system decrease. Figure 6 also shows the breakdown voltage of the LN$_2$/insulation barrier is always higher than the LN$_2$’s with the increased heat power. For the same condition, the positive polarity breakdown always higher than the negative polarity breakdown voltage. In figure 6 (a), is shows as heat power increases, the positive polarity breakdown voltage $V_{B^+}$ of the LN$_2$ decreases sharply at the beginning. Then the positive polarity breakdown voltage $V_{B^+}$ decreases slowly. However, with the heat power increases, the positive polarity breakdown voltage $V_{B^+}$ of the LN$_2$/insulation barrier composite system decrease slower than the LN$_2$’s. The higher the input heat power is, the bigger difference between LN$_2$/insulation barrier system positive polarity breakdown voltage and LN$_2$ positive polarity breakdown voltage is. When the heat power is 21 W, the breakdown voltage is about 1.5 times higher than the LN$_2$’s. In figure 6 (b), the negative polarity breakdown voltage $V_{B^-}$ of the LN$_2$ decreases sharply at the beginning with the heat power increases. Then the negative polarity breakdown voltage $V_{B^-}$ of the LN$_2$ nearly maintain to a certain level. Sauer’s [11] suggested there may be a “vapor bridge” formed between the two electrodes. While for the LN$_2$/insulation barrier composite system, the thermal bubbles nearly have no influence on the negative breakdown voltage of it. In the presence of thermal bubbles, the negative polarity breakdown of the LN$_2$/insulation barrier system is about 1.5 times larger than the LN$_2$’s.

3.1.2. Simulation results

To verify the experiment, a 2D simulation has been made. The electric field distributions for different conditions was shown in figure 7. The parameters of the electrodes and the insulation barrier were shown in Table 1. The voltage applied to the electrodes is 40 kV. Bubbles do affect the field distribution inside and around them. Figure 7(a) and (b) shows that the electric field of LN$_2$ with bubble is higher than that without the bubble. Hara et.al [20] suggest under non-uniform field, partial discharge was followed by breakdown in bubbles exposed to an extremely high electric field. Furthermore, the discharge field strength of the gas nitrogen is smaller. Thus, the bubbles would decrease the breakdown strength.
When there is not an insulation barrier between the two electrodes. Maybe some bigger bubbles will move into the gap of the rod-plane electrodes. Comparing Figure 7 (b) and (c) shows the bigger the bubble is, the higher the electric field is. When an insulation barrier inserts into the rod-plane electrode, the bubble only move to the rod electrode and the insulation barrier side. The insulation barrier prevents the bubbles forming the “vapor bridge” between the rod-plane electrodes. This may increase the insulation strength of the LN$_2$/insulation barrier composite system.

**Conclusion**

Barrier effect on the DC breakdown characteristics of liquid nitrogen with bubbles was investigated. The results are revealed as followings.

1) The DC breakdown voltage of the LN$_2$/insulation barrier composite system is higher than the LN$_2$ regardless of the presence of the bubbles. The DC breakdown voltage of the LN$_2$/insulation barrier system is about 1.5 times higher than the LN$_2$ in the presence of the bubbles for both of the positive and negative polarities.

2) The 2D electric filed simulation for different conditions was done. The results shown that bubbles do affect the field distribution inside and around them seriously. The bigger bubble is, the higher electric field is. Thus, the bubbles may the main factor to induce the breakdown. The insulation barrier inserted into the rod-plane electrodes prevent the bubbles forming the “vapor bridge”. This maybe the reason for enhancing the insulation strength.

3) The barrier effect could not only improve the insulation strength of the normal state but also the quenching state of the R-SFCL.

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