Volume Effect of Dynamic Breakdown Strength in LN_2 for Insulation Design of Resistive Superconducting Fault Current Limiters

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***Abstract*—Toward the practical and rational insulation design of resistive superconducting fault current limiter (SFCL), it is necessary to consider the electrical breakdown (BD) due to transient bubble generation in liquid nitrogen (LN_2) at the quench of HTS materials. We have been investigating the intrinsic BD characteristics of LN_2 without bubbles and the dynamic BD characteristics of LN_2 under transient bubble disturbance, respectively. In this paper, we investigated the dynamic BD characteristics of LN_2 for different electrode diameters and gap lengths, and discussed in terms of the volume effect of dynamic BD strength.**

***Index Terms*—superconducting fault current limiters, quench, liquid nitrogen, bubble, breakdown, insulation design**

I. INTRODUCTION

SUPERCONDUCTING fault current limiters (SFCL) have been expected for power transmission and distribution systems in a high-density demand area. The resistive SFCL has been developed around the world because of its rapid and effective current limitation with simplicity and compactness [1]–[3]. However, as one of the technical problems of resistive SFCL, electrical breakdown (BD) characteristics of liquid nitrogen (LN_2) under the fault current limiting operation with transient bubble disturbance are crucial.

When fault current flows in resistive SFCL, a quench of HTS materials may occur and generate bubbles in LN_2. As the result, BD can be induced by the bubbles under the operating voltage of SFCL. We call such BD a “dynamic BD”. On the other hand, we call BD without bubbles an “intrinsic BD”. The dynamic BD characteristics of LN_2 are important and peculiar to the insulation design of resistive SFCL.

As the BD characteristics of LN_2 under bubble disturbance, most researchers have investigated the BD characteristics with continuous thermal stress [4]–[6]. Since the bubble disturbance in resistive SFCL is the transient phenomena during the fault current limitation, the insulation design based on the BD characteristics with continuous thermal stress may be conservative or pessimistic. Then, the insulation design based on the dynamic BD characteristics with transient thermal stress will contribute to the rational development of resistive SFCL.

From the above background, we have been investigating the fundamental dynamic BD characteristics of LN_2 for different transient thermal stress, LN_2 pressure, etc., and suggested a flowchart of rational and reliable insulation design of resistive SFCL based on the dynamic BD characteristics of LN_2, as shown in Fig. 1 [7][8]. In this paper, we investigated the dynamic BD characteristics of LN_2 for different electrode diameters and gap lengths. In addition, we discussed the dynamic BD characteristics in terms of the volume effect of the dynamic BD strength for the practical and rational insulation design of resistive SFCL.

II. EXPERIMENTAL SETUP AND METHODS

Fig. 2 shows the experimental setup. The cryostat has a FRP (fiber reinforced plastic) capacitor bushing, which is PD free at 150 kV_{rms} in LN_2. The test sample configuration is shown in Fig. 3. The test sample is composed of a high-voltage rod or sphere electrode and a grounded sheet electrode. With the diameter ϕ = 6 mm and 20 mm of high-voltage electrode and the gap length g = 2 mm - 7 mm between the high-voltage and grounded electrodes, the field utilization factor ζ = 0.88-0.40 is arranged. The grounded sheet electrode is made of nichrome

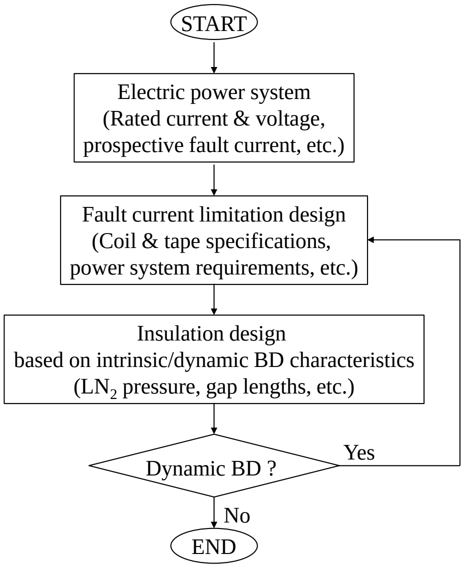

Fig. 1 Flowchart of insulation design for resistive SFCL [8]

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and cut into a meander shape, which acts as a heater with the resistance of 2 Ω to generate bubbles by the thyristor-controlled voltage source.

Two kinds of BD tests were carried out for different electrode diameters and gap lengths in LN_2 at the temperature of 77 K and the pressure of 0.1 MPa.

1. *Intrinsic BD test without bubbles*

   AC high voltage V_a of 60 Hz was applied to the high voltage electrode and ramped at the increasing rate of 1 kV_{rms}/s in order to measure the intrinsic BD voltage without bubbles. It was measured 20 times repeatedly at the same condition. In addition, the intrinsic BD voltage with 50 % probability ($V_{intrinsic}$) was calculated by the 2-parameter Weibull analysis, and it was converted to the intrinsic BD strength with 50 % probability ($E_{intrinsic}$) at the tip of the high voltage electrode with the maximum electric field strength.

2. *Dynamic BD test with transient bubble disturbance*

   At the applied and kept voltage V_a below $V_{intrinsic}$, the nichrome sheet electrode was energized to generate bubbles with the current of 8 A_{rms} during 1 s. This current level corresponds to the heater power density of 5.12 W/cm^2, which is consistent with the ohmic energy level to be generated at the quench of superconducting tapes for resistive SFCL. The applied voltage was reduced to 0 after each test and increased again to V_a for the next test at least 1 min after the previous test. This test procedure was repeated 20 times for a fixed V_a, and the generation probability of dynamic BD was obtained. This operation was repeated for different V_a to get the dynamic BD probability at each V_a. The dynamic BD strength with 50 % probability ($E_{dynamic}$) was calculated by the relationship between the BD probability and V_a.

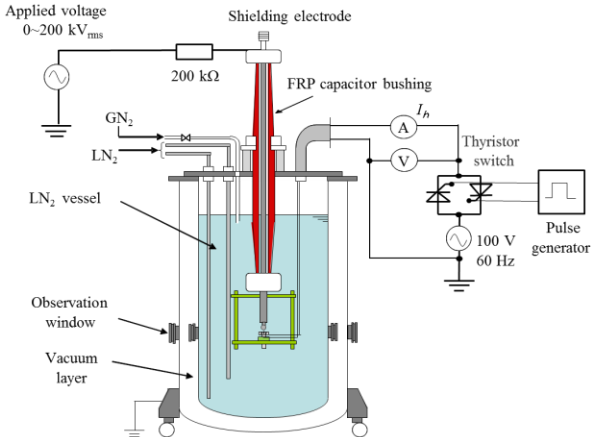


Fig. 2 Experimental setup

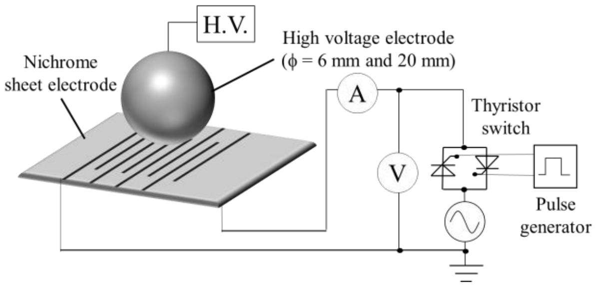


Fig. 3 Test sample configuration

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Gap length dependence and volume effect of intrinsic breakdown strength*

Fig. 4 shows the gap length dependence of $E_{intrinsic}$ in LN_2 for different electrode diameters (ϕ = 6 mm and 20 mm). The error bars represent the standard deviation. In Fig. 4, $E_{intrinsic}$ decreased with the increase in the gap length for both electrode diameters. In addition, $E_{intrinsic}$ at ϕ = 20 mm is lower than $E_{intrinsic}$ at ϕ = 6 mm. This is attributed to the volume effect of BD strength in LN_2 [9], where the number of weak points on electrical insulation such as micro bubbles would increase with the increase in the stressed liquid volume.

The data of $E_{intrinsic}$ at $\zeta > 0.6$ in Fig. 4, i.e. all plots for ϕ = 20 mm and one plot at g = 2 mm for ϕ = 6 mm, are selected for quasi-uniform electric field and plotted in the systematized volume effect of BD strength in LN_2, as shown in Fig. 5. α %

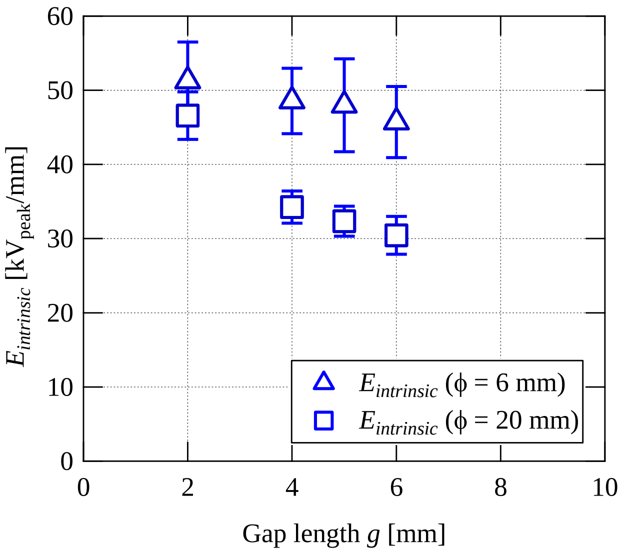


Fig. 4 Gap length dependence of intrinsic BD strength $E_{intrinsic}$ in LN_2

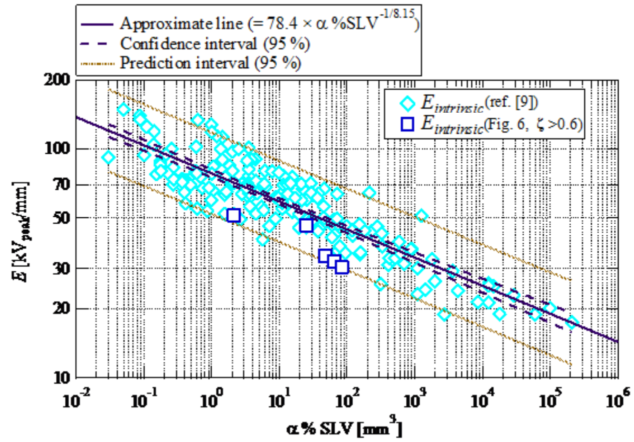
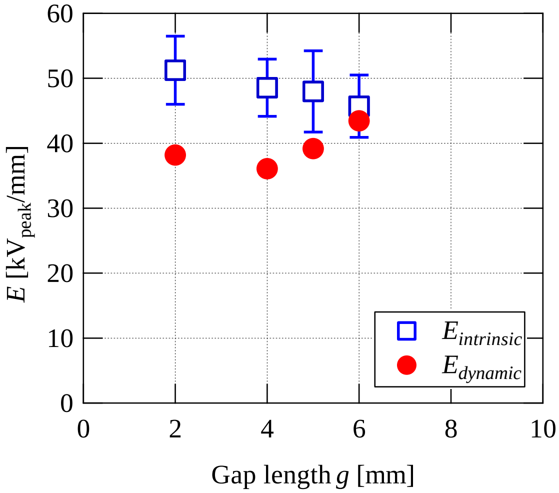


Fig. 5 Volume effect of intrinsic BD strength $E_{intrinsic}$ in LN_2

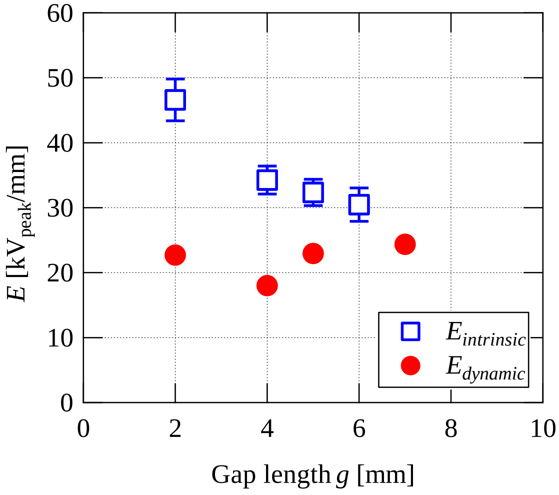
SLV on the horizontal axis means the stressed liquid volume (SLV) with the electric field strength higher than α [%] of the maximum strength [9]. The value of α depends on the temperature and pressure of LN_2, e.g. α = 81 % at 77 K and 0.1 MPa [9]. $E_{intrinsic}$ in Fig. 5 were lower than the approximate line, but located within the prediction interval (95 %) in Fig. 5. Therefore, $E_{intrinsic}$ in Fig. 5 can be regarded to be consistent with the systematized volume effect of BD strength in LN_2.

B. Gap length dependence and volume effect of dynamic breakdown strength

Fig. 6 shows the gap length dependence of $E_{intrinsic}$ and $E_{dynamic}$ in LN_2 for different electrode diameter (ϕ = 6 mm and 20 mm). In the gap length shorter than g = 4 mm at ϕ = 6 mm in Fig. 6 (a), $E_{dynamic}$ was lower than $E_{intrinsic}$ and decreased with the increase in the gap length. However, $E_{dynamic}$ changed to increase at g > 4 mm and approached $E_{intrinsic}$ at g = 6 mm. The similar decrease and increase in $E_{dynamic}$ was also obtained at ϕ = 20 mm in Fig. 6 (b). The decrease in $E_{dynamic}$ suggests the volume effect of BD strength under the dynamic or transient bubble disturbance. On the other hand, the increase in $E_{dynamic}$ suggests that the transient bubble disturbance does not affect the BD strength in LN_2 at the larger gap lengths.



(a) ϕ = 6 mm



(b) ϕ = 20 mm

Fig. 6 Gap length dependence of intrinsic BD strength $E_{intrinsic}$ and dynamic BD strength $E_{dynamic}$ in LN_2

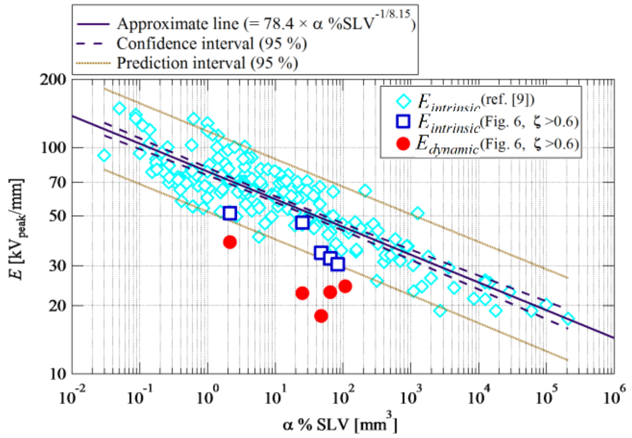


Fig. 7 Volume effect of intrinsic BD strength $E_{intrinsic}$ and dynamic BD strength $E_{dynamic}$ in LN_2

$E_{dynamic}$ at ζ > 0.6 in Fig. 6 are also added in Fig. 5, as shown in Fig. 7. In Fig. 7, $E_{dynamic}$ were lower than the bottom of the prediction interval (95 %) of $E_{intrinsic}$ and decreased with the increase in α % SLV.

Fig. 8 shows the gap length dependence of BD voltages $V_{dynamic}$ and $V_{intrinsic}$ with and without bubble disturbance in LN_2 by Karlsruhe Institute of Technology (KIT), Germany [10], with a larger high-voltage sphere (ϕ = 50 mm) and longer gap lengths (g ≤ 90 mm). A heater with the power of 500 W was installed on the back side of the grounded plane electrode and energized for 12 s, i.e. the heater power density was 4.42 W/cm^2, which is in the same level as 5.12 W/cm^2 in our experiments.

Since the experimental methods in Fig. 8 are different but similar to our experiments, especially on the heater power density, we converted $V_{intrinsic}$ and $V_{dynamic}$ at g < 25 mm (ζ >

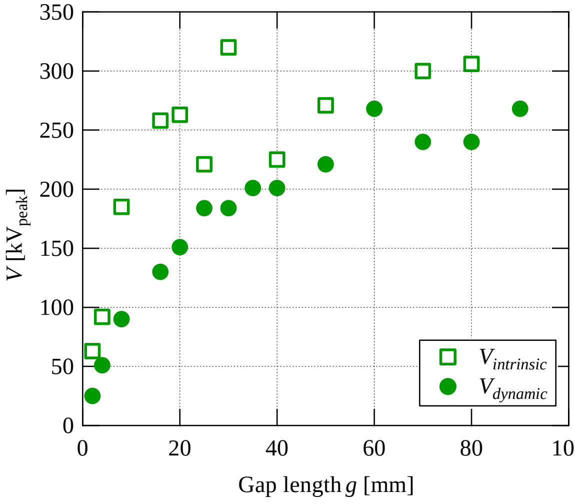


Fig. 8 Gap length dependence of BD voltage in LN_2 at the larger gap length

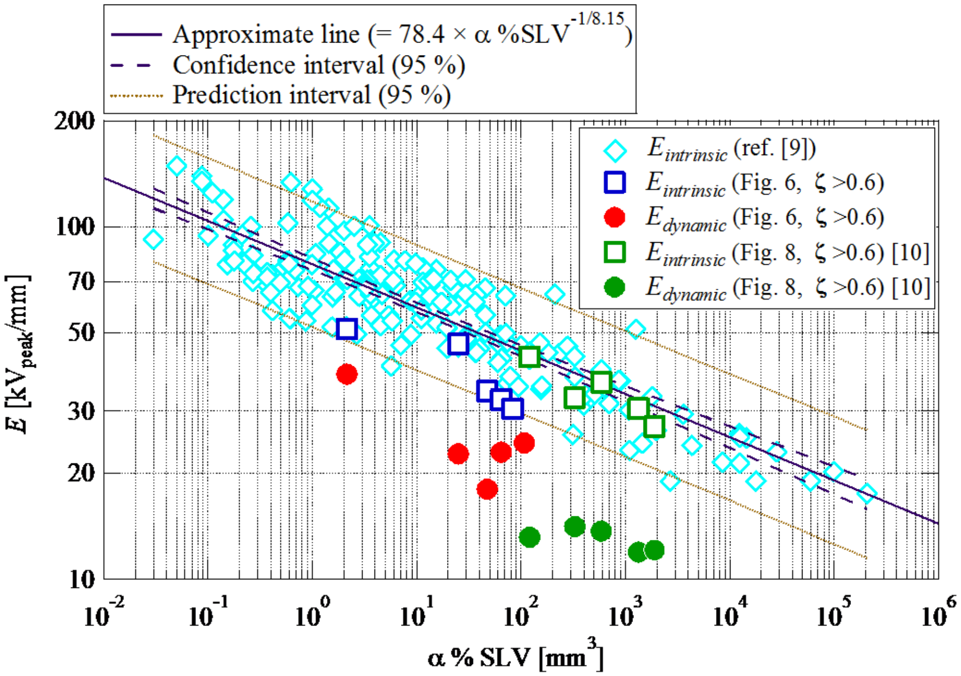


Fig. 9 Volume effect of intrinsic BD strength $E_{intrinsic}$ and dynamic BD strength $E_{dynamic}$ in LN_2 with the data in Fig. 8

0.6) in Fig. 8 into BD strengths $E_{intrinsic}$ and $E_{dynamic}$, and added in Fig. 7, as shown in Fig. 9. In Fig. 9, all plots of $E_{intrinsic}$ located within the prediction interval (95 %), $E_{dynamic}$ were lower than the bottom of the prediction interval of $E_{intrinsic}$ and decreased with the increase in α % SLV. This means suggests that the volume effect of BD strength can be applied not only for $E_{intrinsic}$ without bubbles but also for $E_{dynamic}$ under dynamic or transient bubble disturbance.

From the above discussion, the practical and rational insulation design of resistive SFCL can be expected in consideration of the volume effect of dynamic BD strength $E_{dynamic}$ as well as the intrinsic BD strength $E_{intrinsic}$ in LN_2.

IV. CONCLUSION

This paper described the volume effect of dynamic BD strength in LN_2 under transient bubble disturbance for resistive SFCL. Experimental results revealed that the dynamic BD strength in LN_2 was lower than the intrinsic BD strength without bubbles and decreased with the increase in the electrode diameter and the gap length under quasi-uniform electric field. Thus, it suggested that the volume effect of BD strength can be applied not only for the intrinsic BD strength but also for the dynamic BD strength under dynamic or transient bubble disturbance. On the other hand, the dynamic BD strength approached the intrinsic BD strength at the larger gap lengths under quasi-uniform electric field, which suggested that the transient bubble disturbance does not affect the BD strength in LN_2 under quasi-uniform electric field. From the above results, the practical and rational insulation design of resistive SFCL can be expected in consideration of the volume effect of dynamic BD strength as well as the intrinsic BD strength in LN_2.

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