Pressure Dependence and Size Effect of LN_2 Breakdown Characteristics under Transient Thermal Stress

N. Hayakawa, *Member, IEEE,* T. Matsuoka, K. Ishida, H. Kojima, *Member, IEEE,* S. Isojima, and M. Kuwata

***Abstract*— Electrical insulation of liquid nitrogen (LN_2) for HTS power apparatus can be categorized in two breakdown (BD) modes. One is the intrinsic or conventional BD of LN_2. The other is the BD of LN_2 with transient bubbles, such as a quench. In this paper, BD characteristics of LN_2 with transient bubbles were investigated for different LN_2 pressures and electrode diameters. Experimental results revealed that the BD strength of LN_2 with transient bubbles was lower than the intrinsic BD strength of LN_2. The difference between the intrinsic BD strength and the BD strength with transient bubbles in LN_2 became smaller with the increase in the LN_2 pressure and electrode diameter. Furthermore, BD characteristics of LN_2 with continuous bubbles were investigated and compared with BD characteristics of LN_2 with transient bubbles. As the result, the insulation design of HTS power apparatus in consideration of their quench condition will be rationalized than the design based on the continuous thermal stress.**

***Index Terms*—electrical insulation, breakdown, liquid nitrogen, quench**

I. Introduction

NOWADAYS, the development of HTS power apparatus reaches the installation in actual power system. However, in order to utilize HTS power apparatus around the world, electrical insulation techniques have not yet been fully established, especially under quench condition due to over current larger than the critical current, which is peculiar to HTS power apparatus [1]. In particular, this is quite important and indispensable for resistive-type superconducting fault current limiters [2]–[4]. A quench affects the BD characteristics of LN_2 because a quench causes thermal bubble disturbance in LN_2.

Other researchers also have been investigating the BD characteristics of LN_2 under thermal bubble disturbance [5]–[8]. However, few of them have investigated the transient phenomena. Therefore, it is essential to understand the BD characteristics of LN_2 under transient thermal stress.

From the above background, we have been investigating the BD characteristics of LN_2 with transient bubbles under quasi-uniform electric field configuration. In this paper, the BD characteristics of LN_2 with transient bubbles were investigated for different LN_2 pressures (0.1–0.2 MPa, 77 K) and electrode sizes (sphere diameter: 6–50 mm, gap length: 2 mm).

N. Hayakawa, T. Matsuoka, K. Ishida, and H. Kojima are with the Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya 464-8603, Japan (e-mail: nhayakaw@nuee.nagoya-u.ac.jp, matuoka@hayakawa.nuee.nagoya-u.ac.jp, ishida@hayakawa.nuee.nagoya-u.ac.jp, kojima@nuee.nagoya-u.ac.jp)

S. Isojima is with Sumitomo Electric Industries, Ltd., Osaka 554-0024, Japan (e-mail: isojima-shigeki@sei.co.jp).

M. Kuwata is with Nissin Electric Co., Ltd., Kyoto 615-8686, Japan (e-mail: Kuwata_Minoru@nissin.co.jp)

II. Experimental Setup and Methods

The experimental setup used in this paper is shown in Fig. 1. The cryostat has a FRP capacitor bushing, which is PD free at 150 kV_{rms} in LN_2, and observation windows installed in four directions. Test samples are shown in Fig. 2. The test samples are composed of a high voltage sphere electrode with diameter ϕ = 6–50 mm and a grounded nichrome sheet electrode with the gap length g = 2 mm, *i.e.* under quasi-uniform electric field with field utilization factor ζ = 0.950–0.674. The nichrome sheet electrode is used to induce a transient thermal stress of bubbles into the gap space exposed to high electric field stress. The nichrome sheet is cut into a meander shape and has a resistance of 2 Ω.

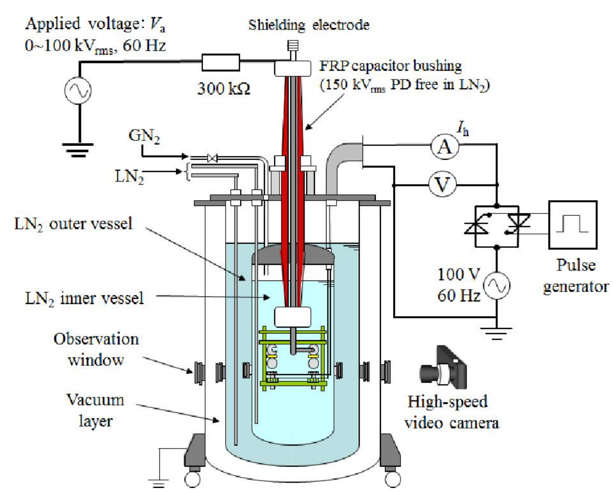


Fig. 1. Experimental setup

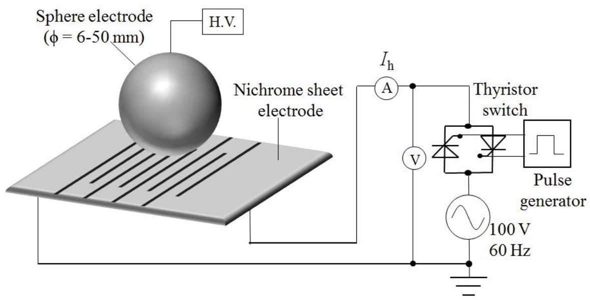


Fig. 2. Test sample configuration

In the above electrode system, we carried out three BD tests for different electrode diameters and pressures of LN_2 with P = 0.1–0.2 MPa at 77 K.

1. *Intrinsic BD test*

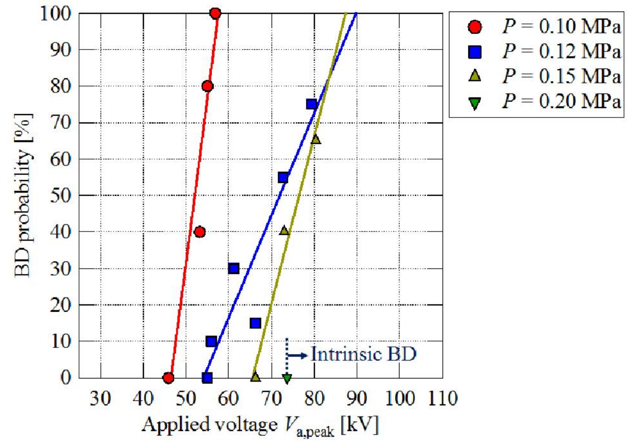
   AC high voltage V_a of 60 Hz was applied to the test sample at the rate of increase of 1 kV_{rms}/s until BD occurred in LN_2 without the bubbles from the nichrome sheet electrode. Intrinsic BD voltage $V_{I\text{-}bd}$ was repetitively measured 20 times and 50% $V_{I\text{-}bd}$ was calculated by the Weibull analysis. 50% $V_{I\text{-}bd}$ was converted to BD electric field strength $E_{I\text{-}bd50}$.

2. *BD test with transient bubbles*

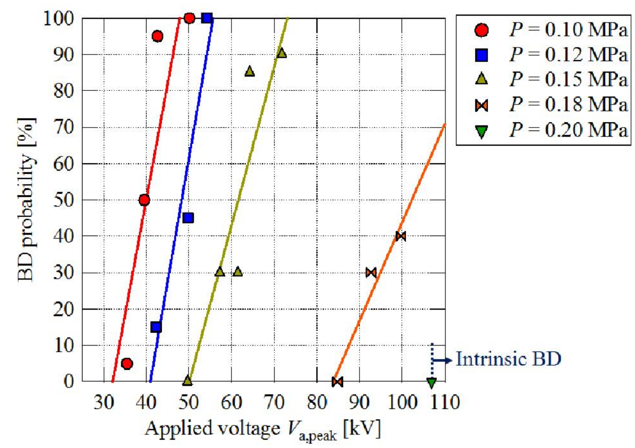
   V_a was applied and kept below 50% $V_{I\text{-}bd}$ to the high voltage electrode. With exposing the test sample to a high electric field stress, thermal stress was superposed by energizing the nichrome sheet electrode with I_h = 8 A_{rms} during 1 s in order to induce BD under bubble disturbance. We carried out this BD test 20 times at the same V_a, and counted the number of BD occurrence to get the BD probability at each V_a. Fig. 3 shows the BD probability of LN_2 with transient bubbles as a function of applied voltage V_a for different LN_2 pressures P at each electrode diameter. The BD probability increased almost linearly around 50% with the increase in V_a, which enabled us to estimate the 50% BD electric field strength $E_{T\text{-}bd50}$ of LN_2 with transient bubbles. At P = 0.2 MPa at each ϕ, the transient bubbles did not induce BD, and intrinsic BD occurred at the higher V_a. This is the reason why there is only one reference point with the BD probability of 0% at P = 0.2 MPa at each ϕ.

3. *BD test with continuous bubbles*

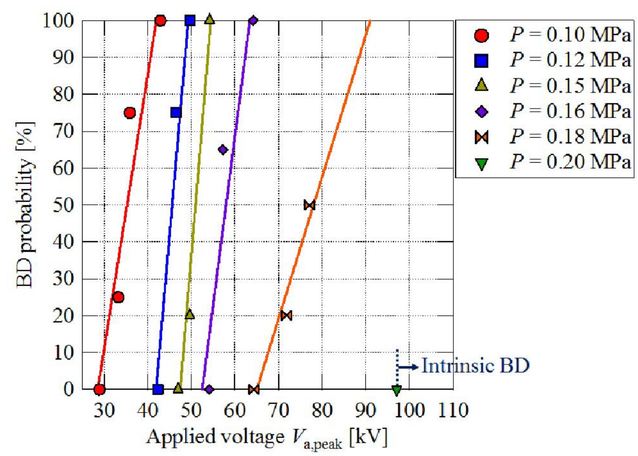
   After the nichrome sheet electrode was continuously energized with I_h = 8 A_{rms}, V_a was applied to the test sample at the rate of increase of 1 kV_{rms}/s until BD occurred in LN_2. As well as the intrinsic BD test, we obtained BD electric field strength of LN_2 with continuous bubbles $E_{C\text{-}bd50}$ by the Weibull analysis with 20 times test at a certain condition.



(a) ϕ = 6 mm



(b) ϕ = 20 mm



(c) ϕ = 50 mm

Fig. 3. BD probability of LN_2 with transient bubbles as a function of applied voltage V_a for different LN_2 pressures P at each electrode diameter ϕ. A plot at each V_a, P and ϕ corresponds to the number of BD occurrence under 20 times tests.

III. Experimental Results and Discussion

A. *Electrode Diameter Dependence*

Fig. 4 shows the electrode diameter dependence of the intrinsic $E_{I\text{-}bd50,peak}$ and the transient $E_{T\text{-}bd50,peak}$ for different LN_2 pressures. Each error bar of $E_{I\text{-}bd50,peak}$ shows the standard deviation. Each

E_{bd50} decreased with the increase in the electrode diameter. The decrease in $E_{I\text{-}bd50,peak}$ is attributed to the increase in the amount of micro bubbles and impurities in LN_2 with the increase in the LN_2 volume of high electric field strength, *i.e.* size effect or volume effect [9]. $E_{T\text{-}bd50,peak}$ at P = 0.1 MPa in Fig. 4(a) is lower than $E_{I\text{-}bd50,peak}$ by 25% at ϕ = 6 mm, and by 50% at ϕ = 20, 50 mm, respectively.

The intrinsic BD characteristics have been systematized in terms of the size effect, *i.e.* the $E_{I\text{-}bd50,peak}$ decreased with the increase in the stressed liquid volume (SLV). $E_{I\text{-}bd50,peak}$ [kV/mm] of sub-cooled LN_2 could be evaluated by α% SLV [mm^3] by the following equation [10],

$$E_{I\text{-}bd50,peak} = 78.4 \times (\alpha\%\ \mathrm{SLV})^{-1/8.15} \qquad (1)$$

where α% SLV is SLV with the electric field strength higher than α% of the maximum strength, and the value of α depends on the pressure and temperature of sub-cooled LN_2. The values of α% SLV for different electrode diameters and LN_2 pressures are exemplified in Table I.

Fig. 4 suggests that the transient BD characteristics with thermal stress may also be interpreted by the size effect. The steeper reduction of $E_{T\text{-}bd50,peak}$ than $E_{I\text{-}bd50,peak}$ at the smaller electrode diameter in Figs. 4 (a)–(c) shows that the size effect of $E_{T\text{-}bd50,peak}$ is stronger than that of $E_{I\text{-}bd50,peak}$. However, the slower inclination of $E_{T\text{-}bd50,peak}$ at the larger electrode diameter tells us the saturation tendency of size effect of $E_{T\text{-}bd50,peak}$, leading to the coincidence with $E_{I\text{-}bd50,peak}$. On the other hand, Fig. 4 (d) shows that $E_{T\text{-}bd50,peak}$ is almost equal to $E_{I\text{-}bd50,peak}$ at P = 0.2 MPa. This may be attributed to the reduced size and number of bubbles, suggesting that the transient bubbles are not harmful to induce BD at these conditions.

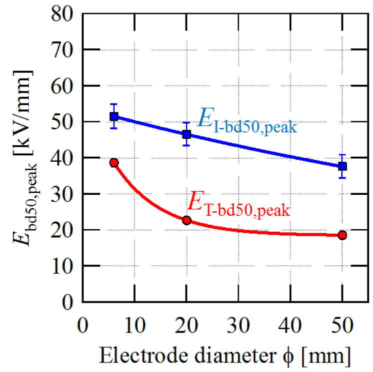
TABLE I
UTILIZATION FACTOR AND α% SLV

Electrode diameter [mm]	Utilization factor	α% SLV @P = 0.1 MPa [mm^3]	α% SLV @P = 0.2 MPa [mm^3]
6	0.674	2.14	1.04
20	0.882	25.1	10.7
50	0.950	120.9	71.3

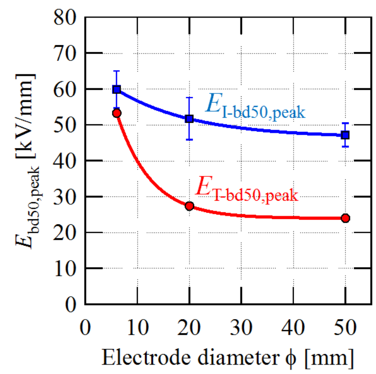
B. Pressure Dependence

Fig. 5 shows the pressure dependence of the intrinsic $E_{I\text{-}bd50,peak}$, the transient $E_{T\text{-}bd50,peak}$, and the continuous $E_{C\text{-}bd50,peak}$ for different electrode diameters. Each E_{bd50} increased with pressure due to the reduced number and size of bubbles. At P > 0.12 MPa for ϕ = 6 mm and at P > 0.15 MPa for ϕ = 20, 50 mm, $E_{T\text{-}bd50,peak}$ is mostly higher than $E_{C\text{-}bd50,peak}$. This may be attributed to the reduced number and size of bubbles under transient bubble disturbance, compared with the continuous bubble disturbance.

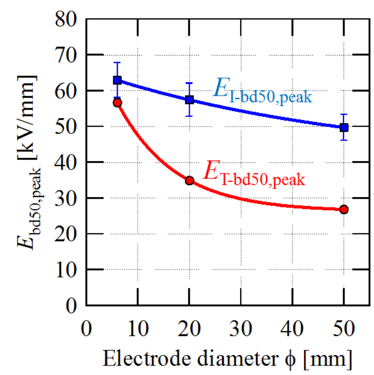
Therefore, the insulation design of HTS power apparatus in consideration of their quench condition will be rationalized than the conservative or pessimistic design based on the continuous bubbles. The BD characteristics of LN_2 with transient bubbles as well as their physical mechanisms will be investigated in more detail, *e.g.* for the longer gap length, the larger thermal stress, and so on.



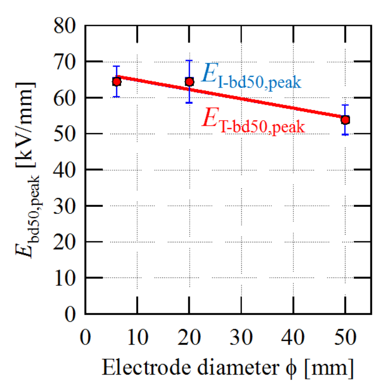
(a) P = 0.10 MPa



(b) P = 0.12 MPa



(c) P = 0.15 MPa



(d) P = 0.20 MPa

Fig. 4. Electrode diameter dependence of $E_{bd50,peak}$

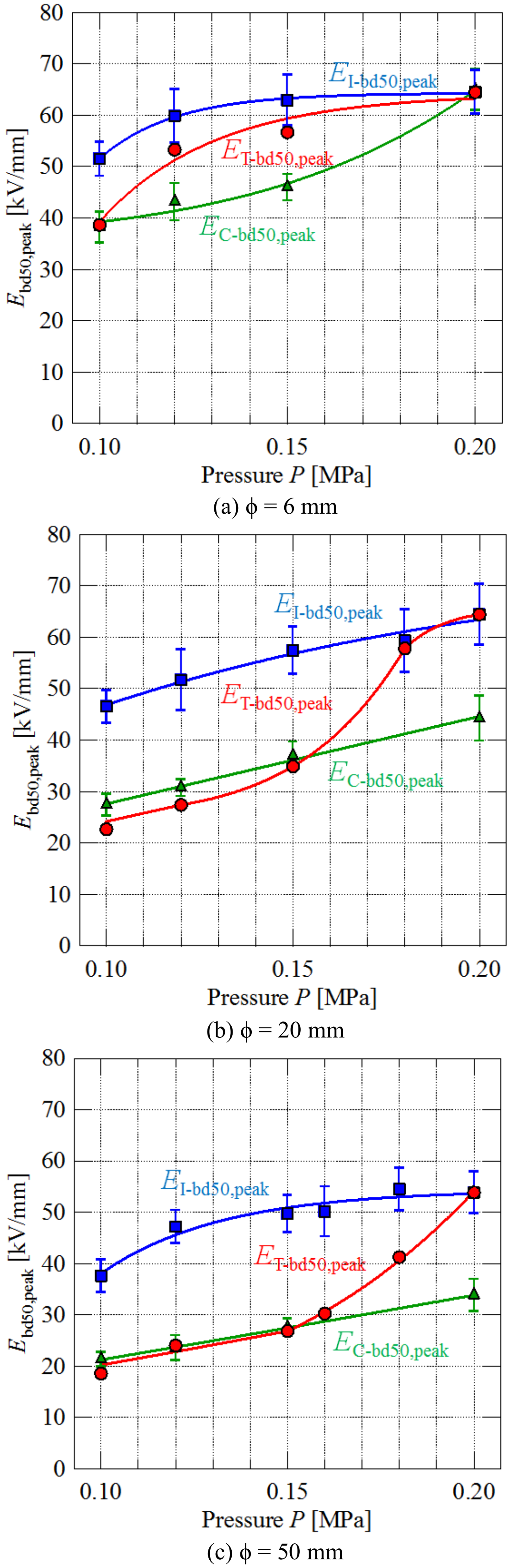


Fig. 5. Pressure dependence of $E_{bd50,peak}$

IV. Conclusion

We investigated the pressure dependence and size effect of the BD characteristics of LN_2 with transient bubbles. The main results in this paper can be summarized as follows:

1. The BD characteristics of LN_2 with transient bubbles may be interpreted by the size effect as well as the intrinsic BD characteristics without bubbles in LN_2.
2. The BD strength of LN_2 with transient bubbles increased in sub-cooled LN_2, where the number and size of bubbles decreased with the increase in pressure.
3. The BD strength of LN_2 with transient bubbles was mostly higher than the BD strength of LN_2 in the continuous bubble disturbance.

The above results suggest that insulation design of HTS power apparatus in consideration of their quench condition will be rationalized than the conservative or pessimistic design based on the continuous bubble generation.

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