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Recent Progress in Electrical Insulation Techniques for HTS Power Apparatus

Naoki Hayakawa*, Hiroki Kojima, Masahiro Hanai, and Hitoshi Okubo

Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

Abstract

This paper describes the electrical insulation techniques at cryogenic temperatures, i.e. *Cryodielectrics*, for HTS power apparatus, e.g. HTS power transmission cables, transformers, fault current limiters and SMES. Breakdown and partial discharge characteristics are discussed for different electrical insulation configurations of LN_2, sub-cooled LN_2, solid, vacuum and their composite insulation systems. Dynamic and static insulation performances with and without taking account of quench in HTS materials are also introduced.

Keywords: HTS power apparatus, electrical insulation, breakdown partial discharge, quench

1. Introduction

For the practical and efficient insulation design and development of HTS power apparatus, electrical insulation techniques at cryogenic temperatures, i.e. "*Cryodielectrics*", have been recognized as one of the fundamental and common techniques [1-3]. Power applications of superconductivity will never be achieved without *Cryodielectrics*. This paper presents our recent progress in *Cryodielectrics* for different insulation components of HTS power transmission cables, transformers, fault current limiters (FCL) and SMES. Breakdown (BD) and partial discharge (PD) characteristics of LN_2 gap, LN_2/solid insulator composite insulation system and vacuum/solid insulator composite insulation system under conduction-cooling are described in terms of the "*static*" insulation performance. Furthermore, in consideration of transient bubble disturbance in LN_2 due to quench, dielectric performance under thermal/electrical combined stress, i.e. "*dynamic*" insulation performance, is discussed for HTS power apparatus with fault current limitation function.

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2. Flowchart for electrical insulation design

Figure 1 shows a flowchart for the electrical insulation design of HTS power apparatus [1]. First, an electric field is calculated for the design specifications. Breakdown stress level is then evaluated in part (a), taking into consideration the area and volume effects [1, 4, 5], as well as the creepage discharge characteristics at the interface between cryogenic liquids and solid insulators. The testing voltage can be determined on the basis of the V-t characteristics in part (b). Breakdown stress is then re-evaluated, taking into consideration the phenomena peculiar to cryogenic environment in part (c), such as quench-induced dynamic insulation performance [6, 7]. In addition, in part (d), safety factors (design margins) are determined, in terms of system coordination and the statistical scattering of discharge phenomena.

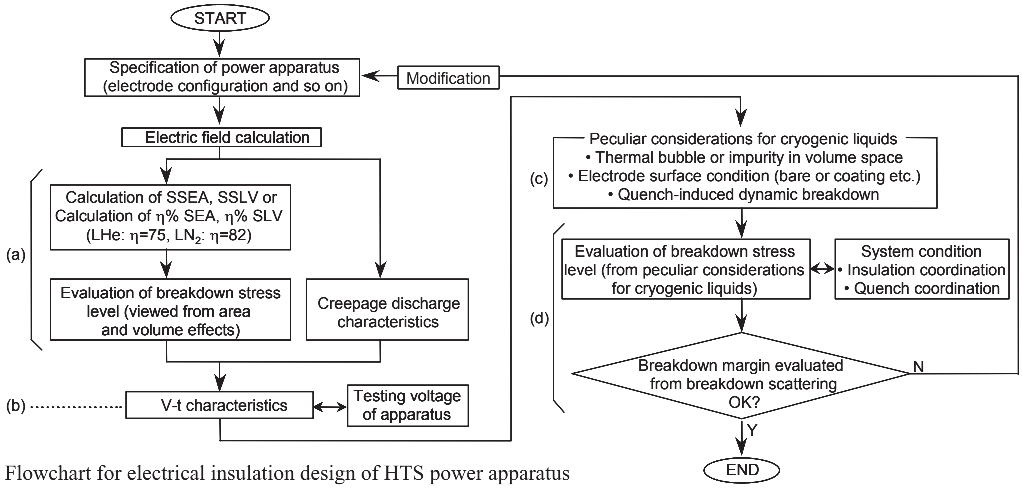

Fig. 1 Flowchart for electrical insulation design of HTS power apparatus
("SSEA" and "SSLV" are statistical stressed electrode area and liquid volume. "η % SEA" and "η % SLV" are stressed electrode area and liquid volume against the maximum electric field strength. "V-t (characteristics)" is "Voltage - time (characteristics)".)

3. Static insulation performance

BD and PD characteristics are fundamental and common to the practical and rational insulation design of HTS power applications. Especially, PD characteristics are crucial for solid insulators in composite insulation systems with LN_2 or vacuum, which may result in insulation degradation and final breakdown. Such fundamental insulation performance is designated as "*static*" insulation performance.

Figure 2 shows the ac BD electric field strength $E_{B(LN2)}$ in LN_2 gap at 77 K and 0.1 MPa (absolute value) as a function of stressed liquid volume (SLV), which is so-called "*volume effect*" [1]. The BD strength decreases into 1/10 with the increase in SLV from 10^{-1} to 10^5 mm^3. Figure 3 shows the pressure dependence of ac BD strength in LN_2 gap [4]. The BD strength increases by the factor of 1.6 from 0.1 to 0.5 MPa for sphere-to-plane electrodes, whereas for coaxial cylinder electrodes it increases twice from 0.1 to 0.2 MPa and then tends to be saturated beyond 0.2 MPa. These results are attributed to the bubbles and impurities in LN_2 as weak points on electrical insulation [4].

PD inception strength (PDIE) of LN_2/polypropylene (PP) laminated paper composite insulation system for HTS cables is investigated in terms of the volume effect with the lowest value at 77 K and 0.1 MPa in Fig. 4 [5], and also systematized for different temperatures (65-77 K) and pressures (0.1-0.3 MPa) of sub-cooled LN_2 in Fig. 5. PDIE increases by the factor of 1.4 from 77 K and 0.1 MPa to 65 K and 0.3 MPa, owing to the bubble suppression and density increase of LN_2. PD inception characteristics are also investigated in vacuum/Kapton film composite insulation system at 20 K, as illustrated in Fig. 6, for double-pancake coil model of conduction-cooled SMES. Figure 7 shows the history of PD inception voltage (PDIV) for different insulation methods and thickness of Kapton film. The increase in PDIV with the increase in the number of voltage application can be interpreted by the so-called "conditioning effect" peculiar to vacuum discharge. The lapped insulation with the thicker film exhibits the higher PDIV due to the relaxation of maximum electric field strength.

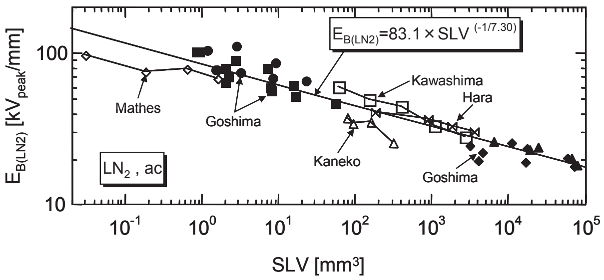

Fig. 2 Volume effect of breakdown strength in LN_2 gap

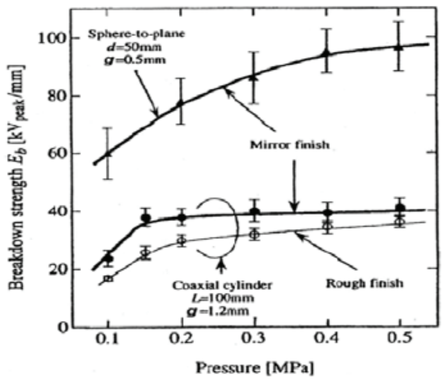

Fig. 3 Pressure dependence of breakdown strength in LN_2 gap

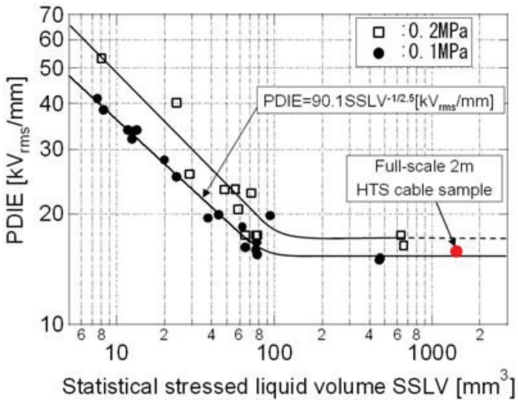

Fig. 4 Volume effect of PDIE in LN_2/PP laminated paper composite insulation system

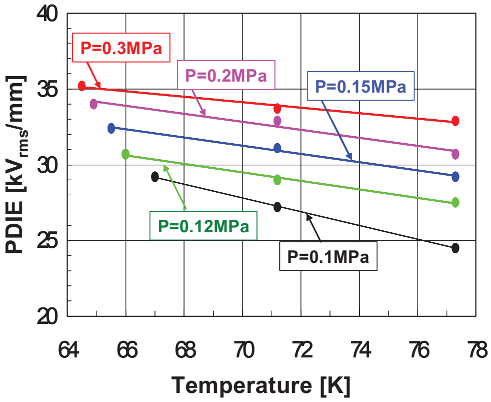

Fig. 5 Temperature and pressure dependence of PDIE in LN_2/PP laminated paper composite insulation system

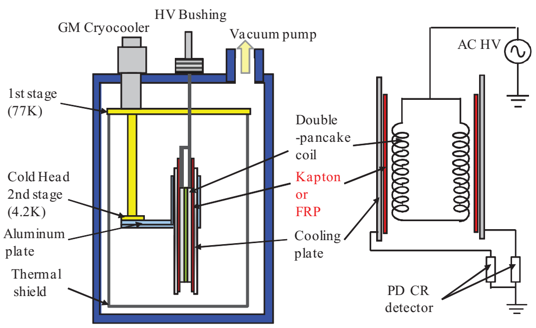

Fig. 6 Experimental setup for PD measurement in vacuum/Kapton composite insulation system at 20 K

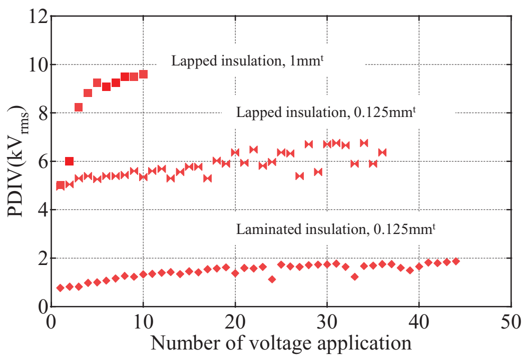

Fig. 7 PDIV in vacuum/Kapton composite insulation system at 20 K

4. Dynamic insulation performance

In the case of e.g. HTS cables under fault condition and resistive-type FCL under current limiting operation, their electrical insulation components are exposed to not only the electric field stress, but also the thermal stress, resulting in the bubble generation in LN_2. Such a transient bubble disturbance in LN_2 is crucial for electrical insulation and referred to as "*dynamic*" insulation performance, against the "*static*" insulation performance in the previous section. The dynamic insulation performance is peculiar to HTS power applications, especially for FCL, FCL transformers (SFCLT) [8] and cables (SFCLC) [9].

Figures 8 and 9 show the dynamic insulation characteristics for LN_2/epoxy [6] and LN_2/PP laminated paper [7] composite insulation system, respectively. The solid lines designate the criteria for PD inception as functions of thermal/electrical combined stress. PD generated under dynamic insulation environment can be extinguished by an effective cooling, but may also be sustained even after the fault clearance and deteriorate the withstand voltage, leading to breakdown.

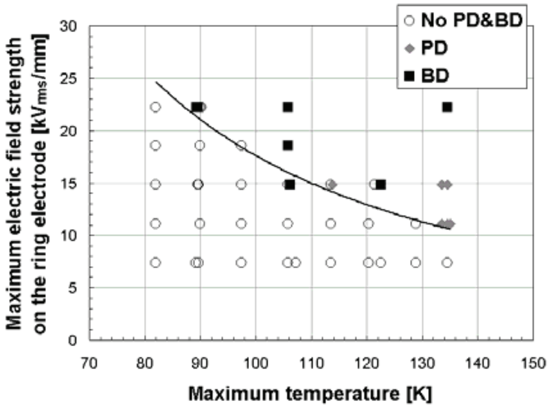

Fig. 8 Dynamic insulation characteristics for LN_2/epoxy composite insulation system

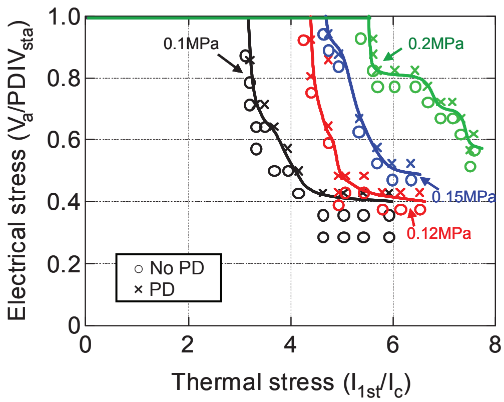

Fig. 9 Dynamic insulation characteristics for LN_2/PP laminated paper composite insulation system
(V_a: Applied voltage, $PDIV_{sta}$: PDIV under static condition, I_{1st}: Current at the 1st cycle after fault, I_c: Critical current)

5. Conclusion

We introduced the recent progress in cryogenic electrical insulation as crucial and common techniques for HTS power apparatus. Breakdown and partial discharge inception characteristics for different insulation components were discussed in terms of static and dynamic insulation performances. The cryogenic electrical insulation techniques should be established and systematized for practical development of efficient and reliable HTS power apparatus.

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