Partial Discharge Inception Strength in a Full-scale HTS Cable Based on LN_2/Polypropylene Laminated Paper Insulation

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***Abstract*- We have been discussing the partial discharge (PD) inception characteristics of liquid nitrogen (LN_2) / polypropylene (PP) laminated paper composite insulation system for high temperature superconducting (HTS) cables. Based on the volume effect on PD inception electric field strength (PDIE) with a parameter called SSLV (Statistical Stressed Liquid Volume), in this paper, we evaluated PDIE of a full-scale HTS cable sample. Experimental results revealed that PDIE of the full-scale HTS cable sample at atmospheric LN_2 pressure under ac voltage application was consistent with the minimum PDIE value in the previous experiments. These results verify that 17.4 kV_{rms}/mm obtained in this paper can be regarded as a criterion of PDIE in consideration of the volume effect for the practical insulation design of actual HTS cables.**

I. Introduction

Applications of high temperature superconducting (HTS) cables have been developed and tested in the actual field of electric power systems around the world [1-6]. However, the electrical insulation design and test schemes of the HTS cables have not been established yet. For the reliable and rational insulation design of the HTS cables, partial discharge (PD) inception characteristics of liquid nitrogen (LN_2) / polypropylene (PP) laminated paper composite insulation system should be understood and systematized [7].

From the above background, we have been investigating the PD inception characteristics of LN_2/PP laminated paper composite insulation system for the HTS cables. We have already evaluated the PD inception electric field strength (PDIE) in terms of the volume effect on PDIE, introducing a parameter SSLV (Statistical Stressed Liquid Volume) up to 470 mm^3 [8-10]. In this paper, we extended the investigation of the volume effect on PDIE up to 1500 mm^3 of SSLV, using a full-scale HTS cable sample with the insulation thickness of 8mm and the effective length of 2m, which is for 77 kV class HTS cable. Considering the results, we discussed the volume effect on PDIE for the practical insulation design of actual HTS cables.

II. HTS Cable Insulation

Table I shows the specifications of HTS cable for Super-ACE project in Japan, which has finished successfully in 2006 [1]. Figure 1 shows the construction of LN_2/PP laminated paper composite insulation system of HTS cable. This insulation system is composed of high voltage conductor, semi-conducting layers, PP laminated paper layers and grounded conductor. The volumes composed of butt gaps and micro gaps between PP laminated papers filled with LN_2 can be considered as weak points for electrical insulation because of concentration of electric field derived from difference in permittivity between LN_2 and PP laminated paper.

SSLV is the total sum of small volume unit weighted with its local electric field strength in high electric field space of the cable for effective length, and given as follows [8-9],

Table I
Specifications of HTS cable for Super-ACE project

Item	Specification
Rated voltage	77 kV
Rated current	1 kA
Length	500 m
HTS tape	AgMg sheathed Bi2223 tape
Conductor layer	O.D. 30 mm
Insulation thickness	8 mm
Shield layer	O.D. 50 mm
PVC sheath	O.D. 133 mm

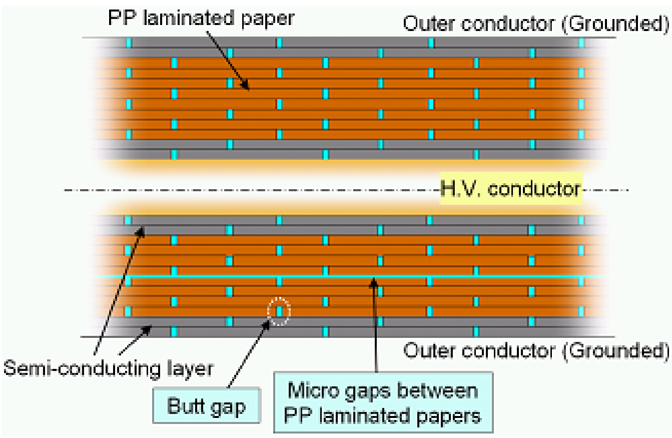

Fig. 1. LN_2/PP laminated paper composite insulation system

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$$SSLV = \iiint_V \left(\frac{E_i}{E_m}\right)^m dv \qquad (1)$$

where E_m is maximum electric field strength, E_i is the electric field strength at a volume unit i, m is the Weibull shape parameter for PDIE, $(E_m/E_i)^m$ corresponds to the relative PD probability at the unit i. In the calculation procedure of SSLV, both the butt gap volume and the volume between PP laminated paper layers are considered, and the shape parameter m is necessary to be experimentally obtained from Weibull plot of PDIE.

III. EXPERIMENTAL SETUP

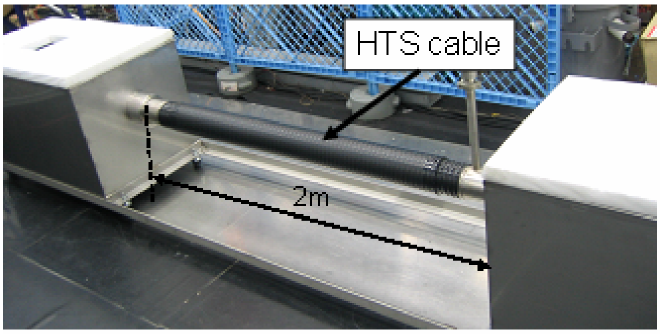
Figure 2 shows the outer view and the cross section of the full-scale HTS cable sample. The effective length of the cable sample is 2m with the total length of 3.2m. The 2m HTS cable sample consists of copper former as an inner cylinder with LN_2 path, superconductor tape (Bi2223), inner semi-conducting layer, PP laminated paper insulation layer (insulation thickness of 8mm), outer semi-conducting layer, shielding mesh tape (cable earth), LN_2 path and superinsulation (thermal insulation layer). This cable sample has stress cones for the electric field grading in both terminals, and was immersed in LN_2 injected from cooling containers at both ends.

Figure 3 shows the experimental setup for the measurement of PD inception characteristics. At atmospheric pressure condition, ac high voltage of 60 Hz was applied to the superconductor tape by 3 kV_{rms}/min. PD signals were detected by CR (Capacitance-Resistance) detector circuits connected with both cable earth and PD tap of bushing, and recorded by a digital oscilloscope. The sensitivity of PD detection system was approximately 25pC. We defined PDIE on the superconductor tape corresponding to the applied voltage at the instant of PD detection.

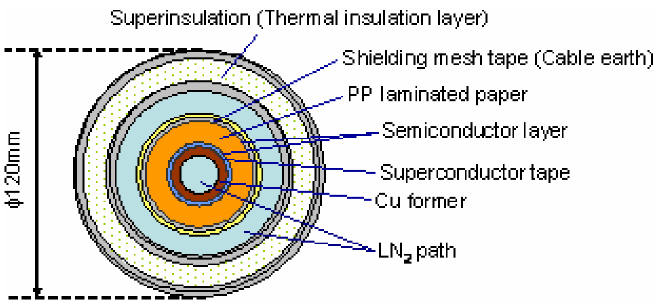
IV. RESULTS AND DISCUSSIONS

Partial discharge inception voltage (PDIV) of the 2m HTS cable sample was 89.1~100.1 kV_{rms}. Figure 4 shows PD signals at PDIV=97.6 kV_{rms} (PDIE=15.2 kV_{rms}/mm); (a) at cable earth, and (b) at PD tap of bushing, respectively. As shown in Fig. 4, PD are generated at around peak phase of the applied ac voltage.

We measured PDIE of the 2m HTS cable sample 13 times and



(a) 2m HTS cable sample



(b) Cross section of 2m HTS cable sample

Fig. 2. Full-scale 2m HTS cable sample

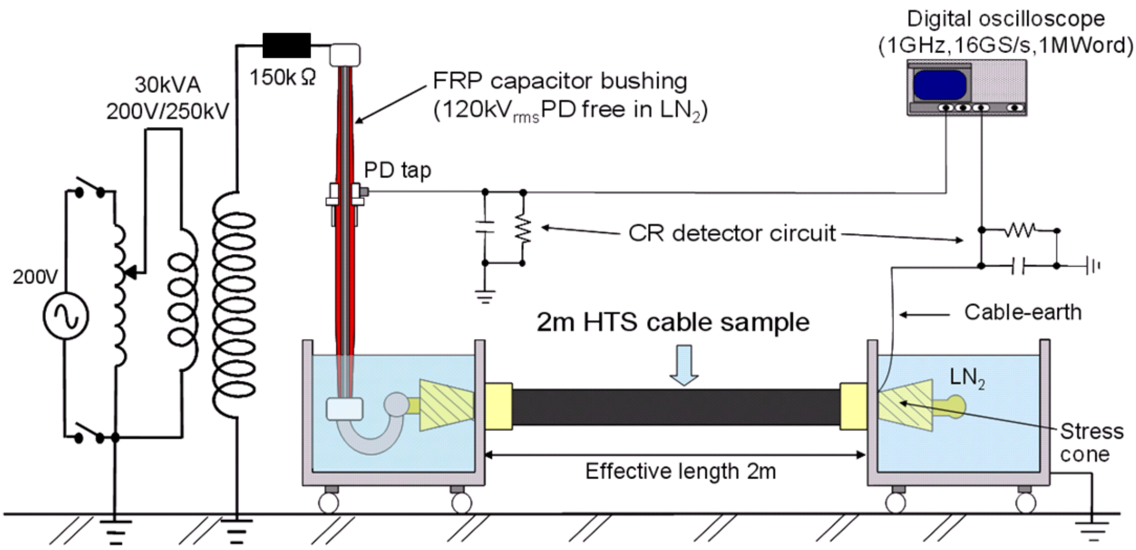
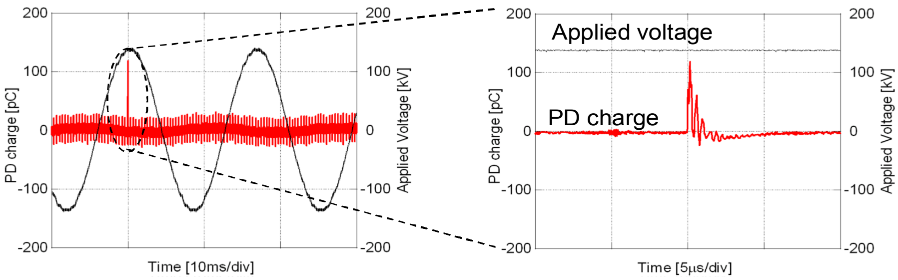
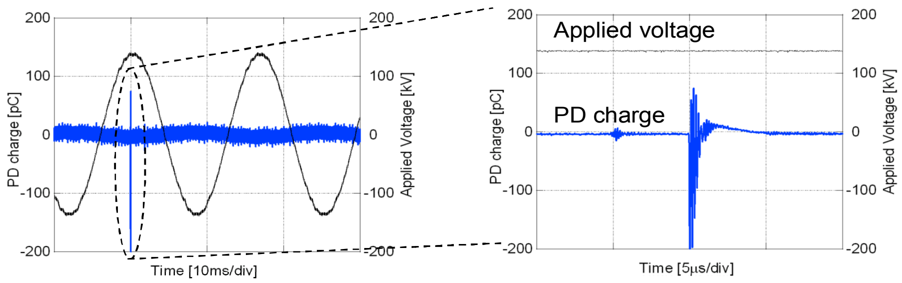


Fig. 3. Experimental setup



(a) at cable earth



(b) at PD tap of bushing

Fig. 4. PD signal waveforms

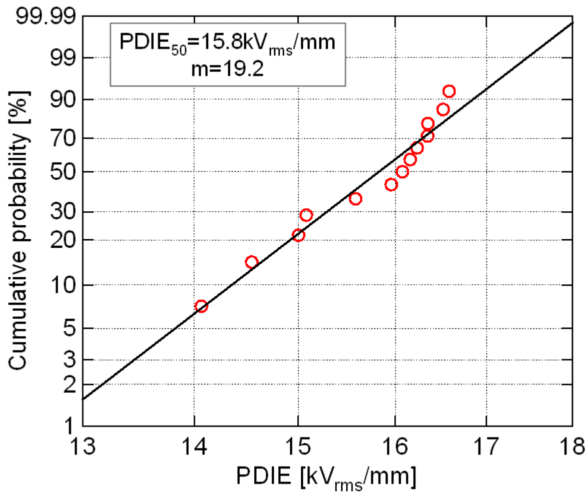


Fig. 5. Weibull plot of PDIE

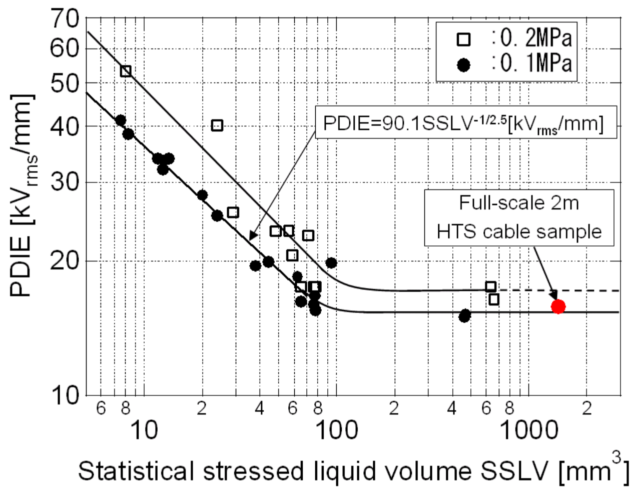


Fig. 6. Volume effect of PDIE

analyzed PDIE statistically based on Weibull distribution. Figure 5 shows Weibull plot of PDIE. The Weibull plot enabled us to determine $PDIE_{50}$, 50% cumulative PD inception probability, as 15.8 kV_{rms}/mm and the shape parameter (m) as 19.2. As the result, SSLV of the 2m full-scale HTS cable sample was calculated as 1423 mm^3.

Figure 6 shows PDIE as a function of SSLV with previous experimental results (SSLV<470mm^3) at atmospheric (0.1MPa) and pressurized (0.2MPa) LN_2 conditions [9]. Previous results reported that PDIE decreased in proportion to $SSLV^{-1/2.5}$ for SSLV<100 mm^3, and was almost constant at about 15 kV_{rms}/mm for 100 mm^3 <SSLV<470 mm^3 at atmospheric LN_2 pressure. On the other hand, SSLV of the 2m full-scale HTS cable sample was 1423 mm^3, which corresponded to about 3 times of the maximum SSLV value in the previous experiments, and PDIE of the 2m full-scale HTS cable sample was 15.8 kV_{rms}/mm. Therefore, PDIE of the full-scale HTS cable sample was consistent with the minimum PDIE value in the previous experiments. These results verify that 15.4 kV_{rms}/mm on the solid curve in Fig. 6 can be regarded as a criterion of PDIE in consideration of the volume effect for the insulation design of HTS cables at atmospheric LN_2 pressure.

Actual HTS cables are expected to be operated at pressurized LN_2 condition; e.g. at above 0.3MPa [1]. According to the previous results on the volume effect on PDIE, as shown in

Fig.6, PDIE at 0.2MPa for 100<SSLV<470 mm^3 was almost constant and minimum at about 17 kV_{rms}/mm, which was 13% higher than that at 0.1MPa. Figure 7 shows the pressure dependence of PDIE for coaxial cylindrical cable samples [11], where PDIE was normalized by that at 0.1MPa. PDIE increased with LN_2 pressure at 0.1~0.2MPa and tended to be saturated at above 0.2MPa. These results enable us to predict that PDIE of the 2m HTS cable sample at pressurized LN_2 can be 17.4 kV_{rms}/mm (=15.4×1.13), which will contribute to the practical and rational insulation design of actual HTS cables.

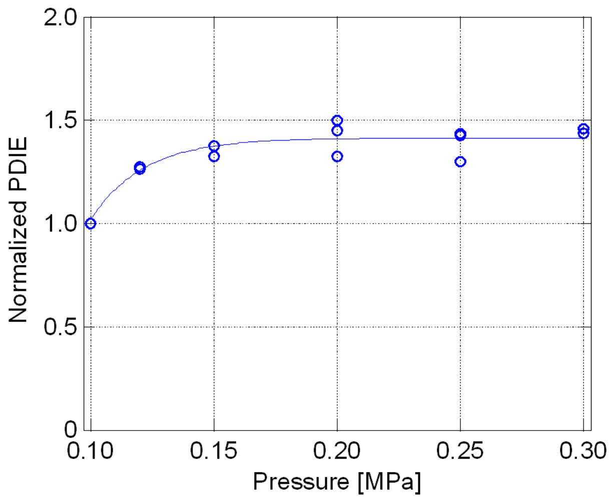


Fig. 7. Pressure dependence of PDIE

V. CONCLUSIONS

In this paper, we extended the investigation of the volume effect on PDIE for SSLV up to about 1500 mm^3 from 470 mm^3 in the previous experiments, using a full-scale 2m HTS cable sample. The main results are summarized as follows:

(1) PDIE in terms of volume effect was almost constant for SSLV>100 mm^3 under atmospheric condition.

(2) The minimum PDIE value in consideration of the volume effect at atmospheric condition was 15.4 kV_{rms}/mm.

(3) At pressurized condition above 0.3MPa, the minimum PDIE value was estimated as 13% higher than that at 0.1MPa; e.g. 17.4 kV_{rms}/mm.

These investigations on the volume effect on PDIE will contribute to the practical, rational and reliable insulation design of actual HTS cables.

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