Partial Discharge Inception Characteristics under Butt Gap Condition in Liquid Nitrogen / PPLP® Composite Insulation System for High Temperature Superconducting Cable

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ABSTRACT

The partial discharge (PD) inception characteristics are studied in liquid nitrogen (LN_2)/polypropylene laminated paper (PPLP®) composite insulation system for high temperature superconducting (HTS) cable. Experimental results revealed that the magnitude of the initial PD increased as the PD inception electric field strength was increased, because the injected energy increased. Initial PD was generated at the first and third quadrant of applied ac voltage phase. The probability of initial PD at the positive and negative voltage phase was almost the same. The reason is because liquid nitrogen is nonpolar molecule and we used symmetric electrode configuration with uniform electric field distribution. Finally, it was pointed out that PD inception electric field strength (PDIE) depended on the volume of the butt gap because of the increasing probability of weak points of electrical insulation, and PDIE linearly decreased with increasing stressed volume of the butt gap in the log-log scale.

1 INTRODUCTION

IN the last ten years, HTS power cables cooling by LN_2 has been increasingly used worldwide [1–4]. In the HTS cable, it is crucial to clarify the partial discharge (PD) inception mechanism in liquid nitrogen/PPLP® composite insulation system. Especially, butt gaps existing in the laminated insulation tapes should be taken into account, because PD may be generated in the butt gap and directly affect the electrical insulation performance [5–9]. Although, volume effects in the breakdown strength in LN_2 have intensely been studied, little is known about PD inception characteristics as influenced by the butt gap volume in LN_2/solid insulation system for HTS power cables [10].

In this paper, we report on the PD inception characteristics as influenced by the volume of the butt gap in liquid nitrogen/PPLP® composite insulation for HTS cable. Especially, we investigated the PD inception characteristics dependence on the number of butt gaps.

2 EXPERIMENTAL

Figure 1 shows the structure of HTS cable developed by Tokyo Electric Power Company and Sumitomo Electric Industries, Ltd. [1]. In Figure 1, for the electrical insulation of HTS cable, PPLP® impregnated with liquid nitrogen LN_2 is used because of the high properties of high insulation strength and low dielectric loss. By taking the electrical insulation layer of the HTS cable as shown in Figure 1 into account, we have made the electrode configuration of LN_2/PPLP® composite insulation system,

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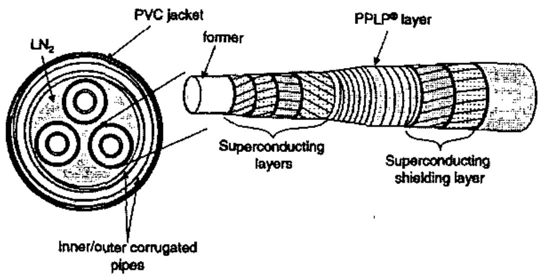


Figure 1. Structure of HTS cable [1].

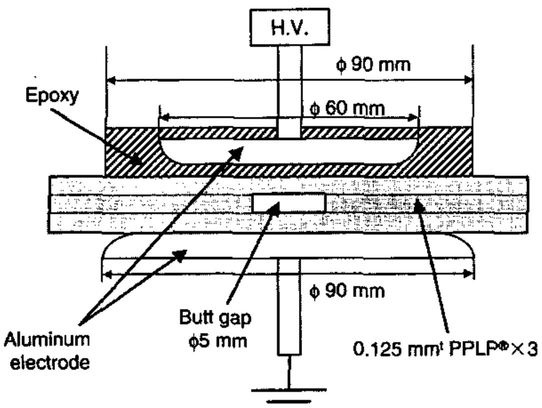


Figure 2. Electrode configuration.

where 3 PPLP® sheets are laminated between parallel plane electrodes, as shown in Figure 2. The diameters of the upper and lower electrodes are 60 mm and 90 mm, respectively. The electrodes are made of aluminum, and the upper electrode is molded with epoxy resin to avoid the edge effect. The diameter of the circular butt gap is 5 mm. The butt gaps are arranged in the middle of the PPLP® layer, as shown in Figure 3. Figure 3 shows the case with 13 butt gaps having a volume of 30.9 mm^3. In this experiment, the butt gap volume is changed by the number of butt gaps. The distance between the butt gaps is kept 2.5 mm. In the experiment, we have measured the PD inception characteristics for 3-layer PPLP® system with 0.125 mm thickness of the butt gap to study the influence of the volume.

Figure 4 shows the experimental setup for the measurement of PD inception of LN_2/PPLP® composite insulation system. A stainless steel cryostat with a fiber glass reinforced plastic (FRP) capacitor bushing, PD free up to 100 kV_{rms} in LN_2, and the LN_2 can be pressurized up to 0.5 MPa. HV 60 Hz is applied to the upper electrode and was increased at a rate of 1 kV_{rms}/s. PD signals are detected through CR detection circuit using digital oscilloscopes with different time scales of 0.5 μs/div and 2 ms/div to measure the PD charge and the voltage phase characteristics, respectively. Measured PD inception voltages (PDIV) are analyzed by using a Weibull plot. Partial

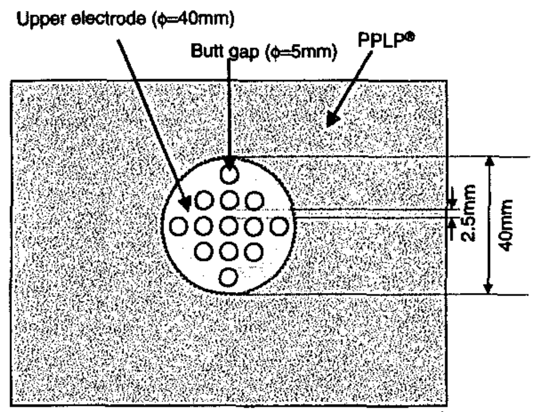


Figure 3. Arrangement of butt gaps at middle PPLP®, layer at SLV = 30.9 mm^3.

discharge inception electric field strength (PDIE) in the butt gap is calculated by taking the permittivities of LN_2 ($\epsilon_{LN2} = 1.45$), PPLP® ($\epsilon_{PPLP} = 2.2$) [8] and epoxy ($\epsilon_{epoxy} = 4.7$) into account. The highest sensitivity of PD detection is 1 pC.

3 PD INCEPTION CHARACTERISTICS

Figure 5 shows typical PD inception characteristics under applied voltage of $V_{ac} = 22.0$ kV_{rms} at stressed liquid volume (SLV) in a butt gap of 30.9 mm^3. The time at the initial PD is defined as t = 0 in Figure 5. Initial PD was 246.7° in the negative polarity of the voltage phase. From highly time-resolve measurement, the initial PD charge is found to be 3.8 pC in Figure 5b. Next, we discuss the PD charge as a function of PDIE at (a) SLV = 2.45 mm^3, (b) SLV = 30.9 mm^3 in Figure 6. Figure 6 indicates that the initial PD charge tends to increase because the injected energy which depends on the electric field strength in the butt gap is increased. PD charges at SLV = 2.45 mm^3 show slightly higher than those at SLV = 30.9 mm^3. The reason may be the higher PD inception voltage at smaller SLV = 2.45 mm^3. There is no difference between the polarity of positive and negative PD in both SLV, because of the uniform electric field strength.

The voltage phase at initial PD for (a) SLV = 2.45 mm^3 and (b) SLV = 30.9 mm^3, is shown in Figure 7. These results lead to the following findings: Firstly, PD generating phase of the initial PD is at the first and third quadrant of voltage phase. Secondly, the phase degree of the initial PD is shifted to the region of 90° at positive PD and 270° at negative PD, as SLV is increased from 2.45 mm^3 to 30.9 mm^3. The main reason is that as SLV is increased, the probability of an initial electron appearance is increased proportionally to the volume of SLV, thus PDIE in a butt gap decreases close to the critical electric field strength in LN_2. Therefore, PD phase is shifted to 90° and PD charge is decreased as SLV is increased.

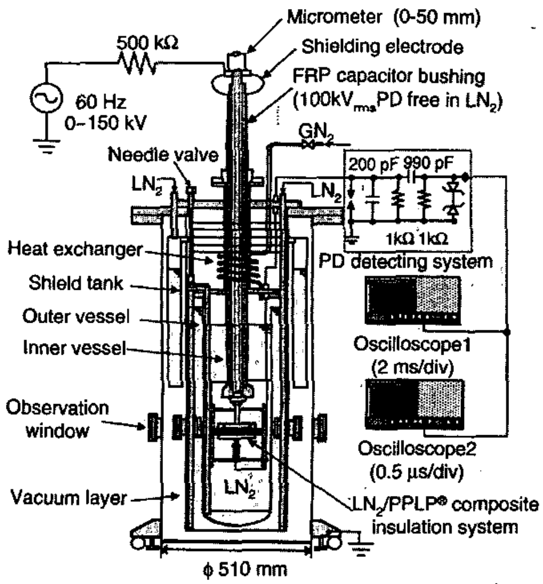
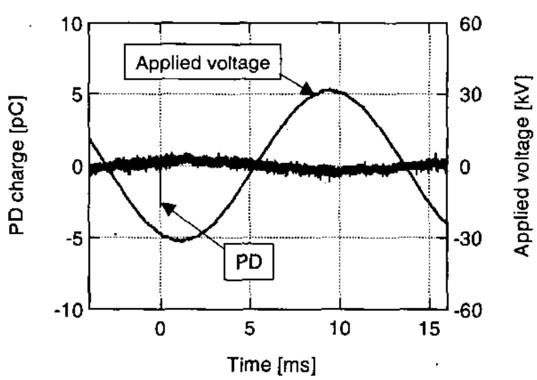
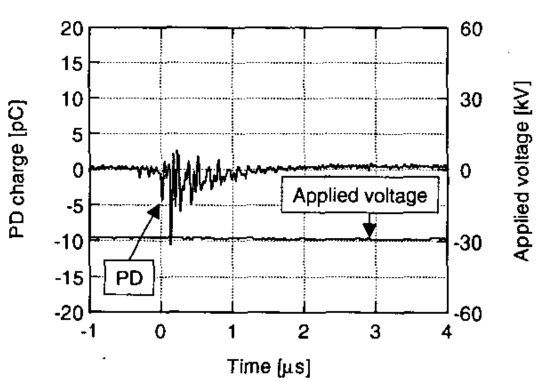


Figure 4. Experimental setup.

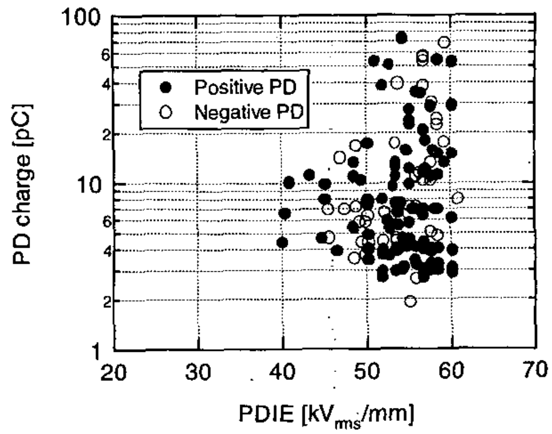


(a) Voltage phase characteristics of PD.

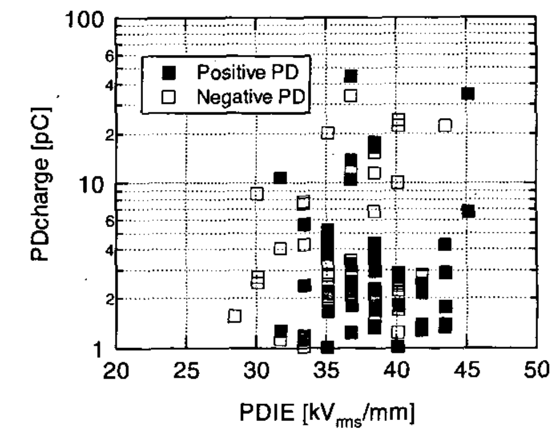


(b) Waveform of first PD.

Figure 5. PD inception characteristics of 3-layer PPLP® system at SLV = 30.9 mm^3. Applied voltage, V_{ac} = 22.0 kV_{rms}; a, Voltage phase characteristics of PD; b, Waveform of first PD.



(a) SLV=2.45 mm^3



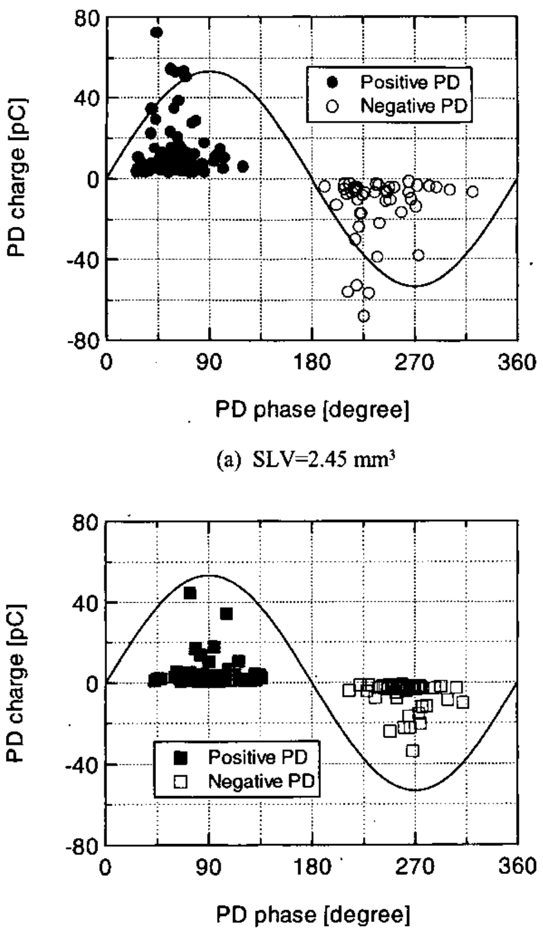
(b) SLV=30.90 mm^3

Figure 6. PD charge as a function of PDIE. a, SLV = 2.45 mm^3 ; b, SLV = 30.90 mm^3.

4 ELECTRIC FIELD STRENGTH OF PD INCEPTION IN BUTT GAP

Figure 8 shows the initial PD generation probability at positive and negative polarity for different SLV in a butt gap. Figure 8 indicates that the initial PD polarity is independent of the different SLV because of symmetric electrode configuration with a uniform electric field distribution. From Figure 8, it can be said that the factor of generated PD would be the same because PD is always generated in the butt gap for different SLV.

Figure 9 shows typical Weibull plots of PDIE in butt gaps for (a) SLV = 2.45 mm^3, (b) SLV = 12.27 mm^3 and (c) SLV = 30.9 mm^3. In these figures, F is the mechanical pressure of PPLP® surface. A reproducibility of PDIE data was confirmed by twice and five times measurements at SLV = 12.27 mm^3 and SLV = 30.9 mm^3 in Figure 9 (b) and (c), respectively. As indicated in these figures, PDIE



(a) SLV=2.45 mm^3

(b) SLV=30.90 mm^3

Figure 7. Voltage phase characteristics of initial PD. a, SLV = 2.45 mm^3; b, SLV = 30.9 mm^3.

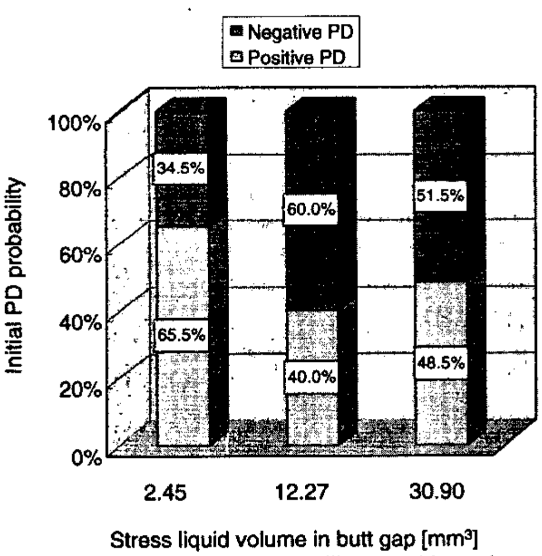
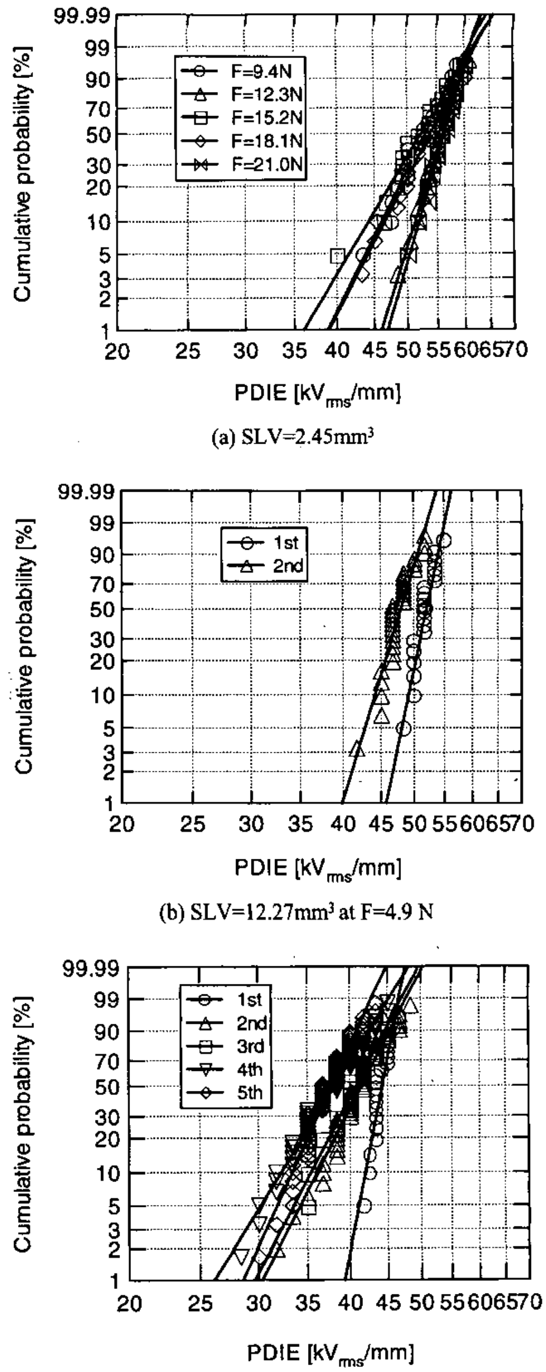


Figure 8. Initial PD generation probability at positive and negative polarity for different SLV.



(a) SLV=2.45mm^3

(b) SLV=12.27mm^3 at F=4.9 N

(c) SLV=30.90mm^3 at F=4.9 N

Figure 9. Weibull plots of PDIE for different butt gap condition. a, SLV = 2.45 mm^3; b, SLV = 12.27 mm^3 at F = 4.9 N; c, SLV = 30.9 mm^3 at F = 4.9 N.

characteristics follow the Weibull distribution and 50% cumulative probability of PDIE ($PDIE_{50}$) is decreased as SLV is increased. We calculate $PDIE_{50}$ and the shape parameter of m_e of PDIE from the Weibull distribution to discuss PD inception characteristics in detail.

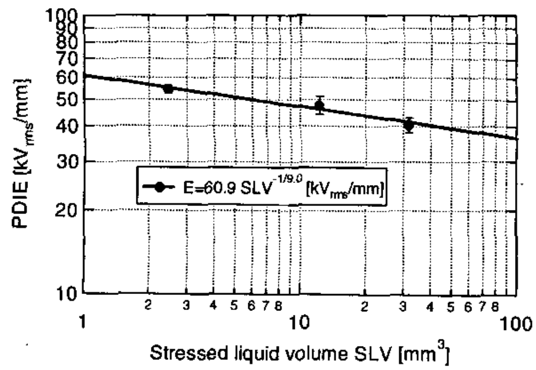


Figure 10. PDIE as a function of SLV in 3-layer PPLP® system.

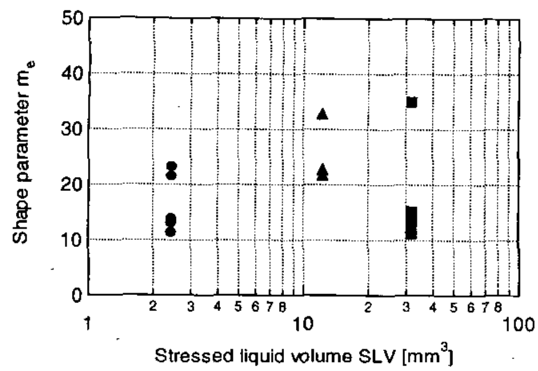


Figure 11. Shape parameter m_e as a function of SLV in 3-layer PPLP® system.

Figures 10 and 11 show $PDIE_{50}$ and m_e for different SLV in a butt gap for 3-layer PPLP® system. In Figure 11, the shape parameter m_e means the dispersion of PDIE and m_e in Weibull distribution is larger as the dispersion of PDIE is smaller. In Figure 10, $PDIE_{50}$ linearly decreases along with the volume of butt gaps in the log-log scale. Approximated equation is obtained as follow,

$$E = 60.9 SLV^{-1/9}. \quad [kV_{rms}/mm] \qquad (1)$$

The volume effect of PDIE must be taken into account in the insulation design of actual HTS power cables.

Let us discuss the experimental results from the shape parameter of PDIE for different SLV in butt gap. From Figure 11, m_e at SLV = 12.27 mm^3 is the largest for three different SLV. The two combined reasons might be considered: one reason is that as the volume of butt gap is increased, the weak points of electrical insulation performance are increased. The other one is that as the butt gap volume increases, PDIE decreases and then the shape parameter m_e decreases because the shape parameter depends on the magnitude of PDIE. Therefore, it can be said that shape parameter m_e at SLV = 12.27 mm^3 becomes the largest from this experiment.

5 CONCLUSION

In this paper, we investigated PD inception characteristics in LN_2/PPLP composite insulation system for HTS cable. Especially, we examined PD inception electric field strength as influenced by the volume of the butt gap. The main results are summarized as follows:

(1) The initial PD charge is in the range 1–60 pC. The charges at smaller volume show slightly higher values.

(2) The PD charge tends to be larger as PDIE increases at all butt gap conditions. The reason is that as PDIE increases, the injected energy which depends on the electric field strength in the butt gap is increased.

(3) The voltage phase of the initial PD generation is independent of the butt gap condition. Almost all PDs are generated at the first and third quadrant of the ac voltage phase. The degree of the initial PD is shifted to the region around 90° at positive PD and 270° at negative PD, as SLV is increased.

(4) The PD generating polarity is independent of SLV. $PDIE_{50}$ linearly decreases along with the volume of the butt gap in the log-log scale.

(5) The shape parameter m_e at SLV = 12.27 mm^3 is the largest for three different SLV. The reason is that firstly, as the volume of the butt gap is increased, the weak points of electrical insulation performance are increased, secondly as the butt gap volume increases, PDIE decreases and then the shape parameter m_e decreases because shape parameter depends on the magnitude of PDIE.

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