V-t Characteristics of Partial Discharge Inception in Liquid Nitrogen/PPLP® Composite Insulation System for HTS Cable

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ABSTRACT

In this paper, we studied partial discharge (PD) inception characteristics and V-t characteristics of PD inception 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 initial PD was in the range of 2.0–30 pC irrespective of butt gap condition and the initial PD was generated at the first and third quadrant of voltage phase. PD inception electric field strength (PDIE) without butt gap was 5–10% higher than that with butt gap and thicker butt gap gave larger PDIE drop. Moreover, PDIE with butt gap depended on the butt gap thickness and the number of PPLP® layers. The reason is explained by the existing probability of weak points of electrical insulation at butt gap. Finally, lifetime indices n of V-t characteristics at PD inception were obtained as 80–100 irrespective of butt gap condition. These values showed enough flat characteristics of V-t phenomena of electrical insulation.

1 INTRODUCTION

In recent years, high temperature superconducting (HTS) power cable cooling by LN_2 has been increasingly used around the world [1–4]. For an electrical insulation design of HTS power cable, it is crucial to understand the partial discharge (PD) inception mechanism in liquid nitrogen/PPLP® composite insulation system. Especially, butt gaps existing within insulation tapes should be taken into account, because PD may be generated in the butt gap and would affect the electrical insulation performance. Although V-t characteristics for breakdown voltage have been an aim of past studies, very few attempts have so far been focused on PD inception characteristics under ac voltage application. The PD mechanism has not been clarified yet and little is known about V-t characteristics for PD inception voltage. Moreover, V-t characteristics of PD inception are very important to establish testing voltage level and estimate the possible life time of electrical insulation in superconducting power cables [5–9]. It should be pointed out that the PD inception characteristics and the V-t phenomena would be the critical parameter of HTS cable insulation.

In this paper, we studied PD inception characteristics and the V-t characteristics as influenced by butt gap thickness in liquid nitrogen/PPLP® composite insulation for HTS cable. Especially, we examined PD inception characteristics influenced by butt gap condition, i.e. butt gap thickness and number of PPLP® layers. Moreover, we studied lifetime indices n of V-t characteristics at PD inception under different butt gap conditions.

2 EXPERIMENTAL

Figure 1 shows the electrode configuration of LN_2/PPLP® composite insulation system, where 3 or 5 PPLP® sheets were laminated between parallel plane

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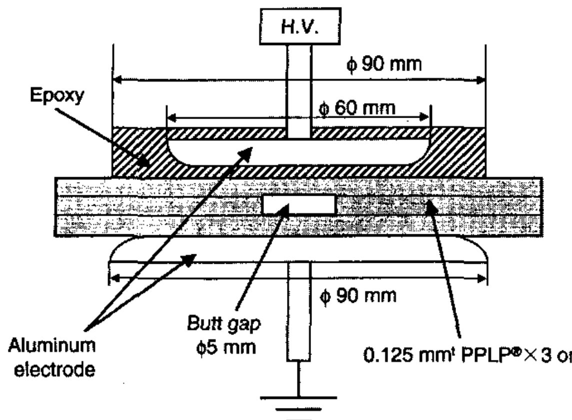


Figure 1. Electrode configuration.

electrodes. The diameters of the upper and lower electrodes were 60 mm and 90 mm, respectively. The electrodes were made of aluminum, and the upper electrode was molded with epoxy resin to avoid the edge effect. A butt gap introduced in the experiment was circular with 5 mm in diameter. For the experiment, we investigated PD inception characteristics under five different cases, i.e., 3-layer PPLP® without butt gap, and with 0.125 mm thickness of butt gap, 5-layer PPLP® without butt gap, and with 0.125 mm, and 0.375 mm thicknesses of butt gap.

Figure 2 shows the experimental setup for the measurement of PD inception and the V-t characteristics of LN_2/PPLP® composite insulation system. The stainless steel cryostat with an FRP capacitor bushing (PD free for 100 kV_{rms} in LN_2), having the ability of pressurizing LN_2 up to 0.5 MPa was used. In this paper, the experimental pressure is 0.1 MPa. 60 Hz HV was applied to the electrodes and increased at a rate of 1 kV_{rms}/s. PD signals were detected through CR circuit by digital oscilloscopes with different time scales of 0.5 μs/div and 2 ms/div to measure the PD charge and the PD phase characteristics, respectively. By setting the electrode system in the cryostat, we measured PD inception voltage (PDIV) and analyzed it using a Weibull plot. PDIE in butt gap is calculated by taking the permittivity of LN_2 (ϵ_{LN_2} = 1.45), PPLP® (ϵ_{PPLP} = 2.2) [8] and epoxy (ϵ_{epoxy} = 4.7) into account. For the case without butt gap, we calculated PDIE in LN_2 assuming an existing thin LN_2 layer in between. We calculated 50% cumulative probability of PDIE ($PDIE_{50}$) from Weibull plot and measured V-t characteristics at PD inception in the range of 110 to 95% of $PDIE_{50}$. The sensitivity of PD detection is lower than 2 pC.

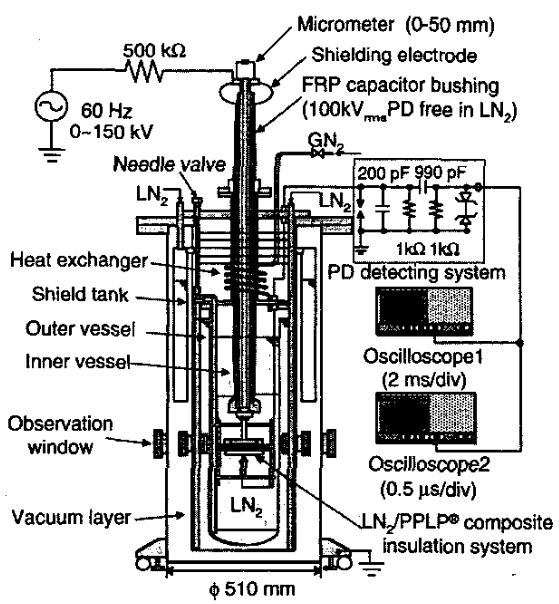


Figure 2. Experimental setup.

3 GENERATING CHARACTERISTICS OF PD INCEPTION

Figure 3 shows a typical result of PD inception characteristics at applied voltage V_{ac} = 34.0 kV_{rms} for the 3-layer

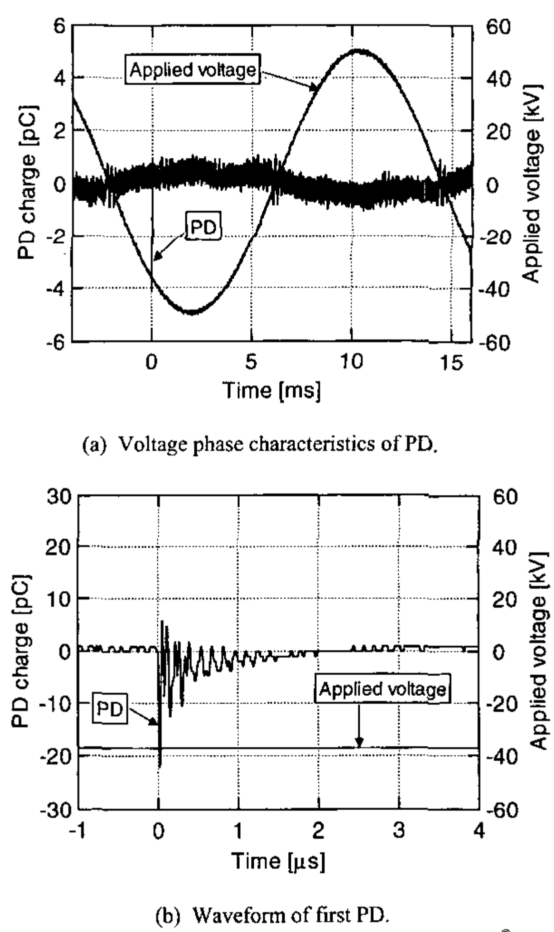


Figure 3. PD inception characteristics of 3-layer PPLP® system without a butt gap. Applied voltage, 34.0 kV_{rms}; a, Voltage phase characteristics of PD; b, Waveform of first PD.

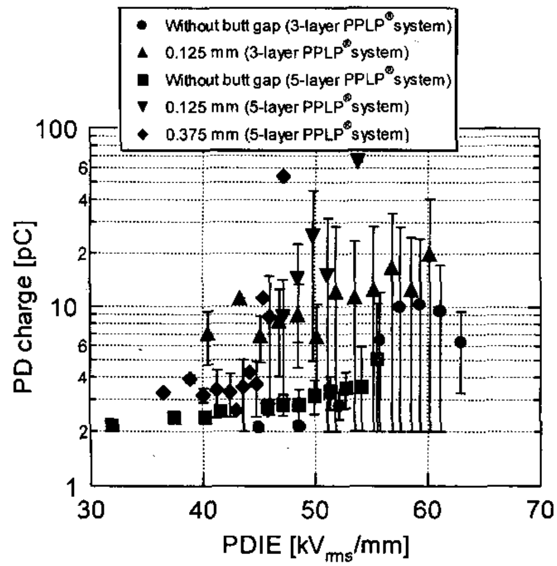


Figure 4. PD charge as a function of PDIE at different butt gap conditions.

PPLP® without butt gap. The time at the initial PD detection is defined as t = 0 ms in Figure 3. Initial PD was 227.6° in the negative polarity of the voltage phase. From highly time-resolved measurement, the initial PD charge was about 22 pC in Figure 3b. Next, we discuss PD charge as a function of PDIE at different butt gap condition as shown in Figure 4. Figure 4 indicates that the initial PD charge is in the range of 2–30 pC and independent of the butt gap condition. It is considered that the PD is generated at LN_2 layer irrespective of with and without the butt gap. Moreover, PD charge is larger as PDIE at all butt gap conditions. The reason is that as PDIE is larger, the injected energy which depends on the electric field strength in the butt gap is increased.

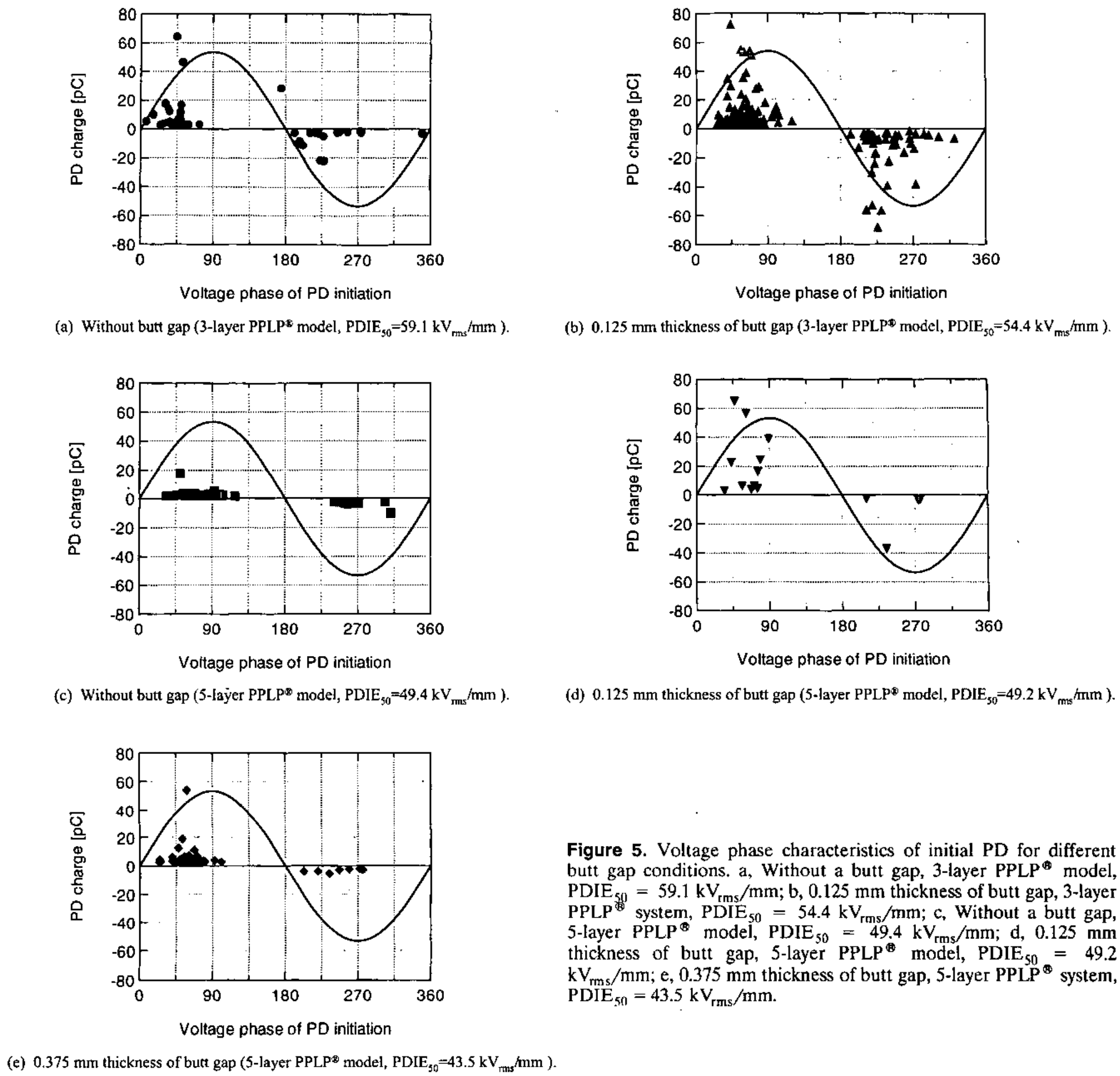
Next, we measured the voltage phase at initial PD generation for (a) 3-layer PPLP® without butt gap, (b) 3-layer PPLP® with 0.125 mm thickness of butt gap, (c) 5-layer PPLP® without butt gap, (d) 5-layer PPLP® with 0.125 mm thickness of butt gap, and (e) 5-layer PPLP® with 0.375 mm thickness of butt gap. These are shown in Figure 5. These results lead to the following: Firstly, most PDs are generated around the voltage peak region, but small part of the PD is generated under lower voltage phase. Secondly, almost all the PDs are generated at the 1st and 3rd quadrant of the voltage phase. The reason might be considered as follows. At first, for PD inception it is needed to satisfy both conditions of electric field strength and initial electron. The probability of initial electron is very small even under ac application because butt gap volume is extremely small. Then, PDIE is highly dependent on the generation probability of electron. If initial electron is not generated, the magnitude of PDIE would be enhanced, and at the same time, the voltage phase-width of PD generation would expand from the peak into the lower voltage phase. At this consideration, 1st and 3rd quadrant phase would equivalently enhance the probability of initial electron generation because the electric field strength in 1st and 3rd quadrants which satisfies the PD generation is kept longer than that in 2nd and 4th quadrants. Therefore, the results of Figure 5 can be well understood.

4 ELECTRIC FIELD STRENGTH OF PD INCEPTION

Figure 6 shows typical Weibull plots of PDIE in butt gap for (a) 3-layer PPLP® and (b) 5-layer PPLP®. In Figure 6, F is the surface mechanical pressure of PPLP®. As shown in Figure 6, PDIE characteristics follow the Weibull distribution and the PDIEs for without butt gap are larger than that for with butt gaps. We have calculated $PDIE_{50}$ and shape parameter of PDIE (m_e) from the Weibull distribution to study the PD inception characteristics in detail.

The values of E_{50} and m_e are summarized in Figures 7 and 8. In Figure 7, firstly, $PDIE_{50}$ for without butt gap (E_{50} = 59.1 kV_{rms}/mm) (A) is 9% higher than that with 0.125 mm thickness of butt gap (E_{50} = 54.4 kV_{rms}/mm) (B) for the 3-layer PPLP®. Secondly, $PDIE_{50}$ for without butt gap (E_{50} = 49.4 kV_{rms}/mm) (C) is almost the same as that with 0.125 mm thickness of butt gap (E_{50} = 49.2 kV_{rms}/mm) (D) and higher than that with 0.375 mm thickness of butt gap (E_{50} = 43.5 kV_{rms}/mm) (E) for the 5-layer PPLP®. Therefore, PD is generated in the butt gap which may be the weak point of the electrical insulation in LN_2/PPLP® composite insulation system. Thirdly, by comparing the data of without butt gap, PDIE for the 3-layer (E_{50} = 59.1 kV_{rms}/mm) is 20% higher than that for the 5-layer (E_{50} = 49.4 kV_{rms}/mm). Fourthly, at 0.125 mm thickness of butt gap, PDIE for the 3-layer (E_{50} = 54.4 kV_{rms}/mm) is 10% higher than that for the 5-layer (E_{50} = 49.2 kV_{rms}/mm). Thus we see that PDIE in butt gap is dependent on the butt gap condition, especially the number of PPLP® layers. The reason is that as the number of PPLP® layer is increased, the volume of LN_2 layer between PPLP® is increased.

Let us discuss the experimental result from the shape parameter of PDIE point of view. Figure 8 indicates that the shape parameter for the 3-layer PPLP® (A) and (B) is almost the same, on the other hand for the 5-layer PPLP®, the shape parameter at 0.375 mm thickness of butt gap (E) is larger than that without butt gap (C) and with 0.125 mm thickness of butt gap (D). Two reasons might be considered. One is that thicker butt gap brings about larger volume and then the weak points of electrical insulation are increased. The other one is that as we have mentioned before, PDIE is especially depended on the number of PPLP® layers because the volume of the butt gap is small. Therefore, without a butt gap and with 0.125 mm thick-



(a) Without butt gap (3-layer PPLP® model, $PDIE_{50}$=59.1 kV_{rms}/mm).

(b) 0.125 mm thickness of butt gap (3-layer PPLP® model, $PDIE_{50}$=54.4 kV_{rms}/mm).

(c) Without butt gap (5-layer PPLP® model, $PDIE_{50}$=49.4 kV_{rms}/mm).

(d) 0.125 mm thickness of butt gap (5-layer PPLP® model, $PDIE_{50}$=49.2 kV_{rms}/mm).

(e) 0.375 mm thickness of butt gap (5-layer PPLP® model, $PDIE_{50}$=43.5 kV_{rms}/mm).

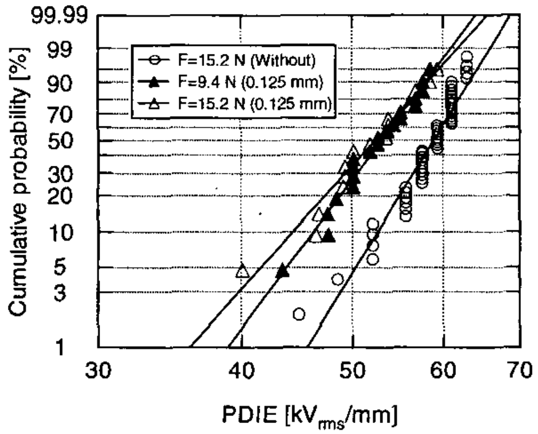
Figure 5. Voltage phase characteristics of initial PD for different butt gap conditions. a, Without a butt gap, 3-layer PPLP® model, $PDIE_{50}$ = 59.1 kV_{rms}/mm; b, 0.125 mm thickness of butt gap, 3-layer PPLP® system, $PDIE_{50}$ = 54.4 kV_{rms}/mm; c, Without a butt gap, 5-layer PPLP® model, $PDIE_{50}$ = 49.4 kV_{rms}/mm; d, 0.125 mm thickness of butt gap, 5-layer PPLP® model, $PDIE_{50}$ = 49.2 kV_{rms}/mm; e, 0.375 mm thickness of butt gap, 5-layer PPLP® system, $PDIE_{50}$ = 43.5 kV_{rms}/mm.

ness of butt gap, it can be said that the shape parameter of PDIE is almost the same. It should be concluded that the PD mechanism in LN_2/PPLP® composite insulation system can be controlled by the butt gap condition.

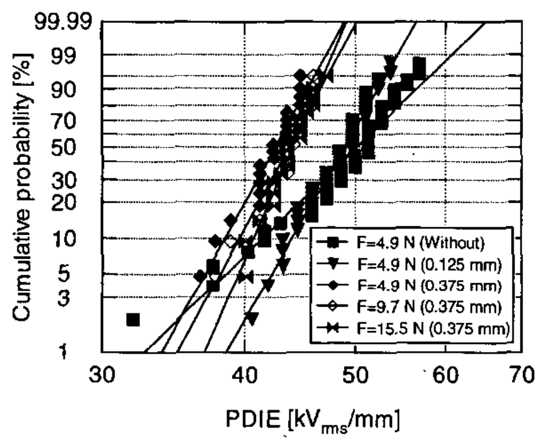
5 V-t CHARACTERISTICS OF PD INCEPTION

We discuss the V-t characteristics at PD inception in butt gaps from the $PDIE_{50}$ obtained in the previous section. The Weibull plots of PD inception time for the 3-layer PPLP® without a butt gap are shown in Figure 9. Table 1 shows the applied electric field strength in the butt gap (E_{ac}), inclination of Weibull plot (m_t) and 50% PD inception time (t_{50}). Figure 9 shows that a regression line can approximate the plots of PD inception time under each voltage application. The shape parameter of the PD inception time is well followed with the Weibull distribution. Furthermore, it can be said that the PD inception characteristics in LN_2/PPLP composite insulation system are initial failure category.

The V-t characteristics at PD inception (F = 15.2 N) for 3-layer PPLP® without butt gap are shown in Figure 10. In Figure 10, the left end indicates the number that did not reach the set electric field strength when PD was generated. The measured points of PD inception time are also shown. As the applied electric field strength is de-



(a) 3-layer PPLP® model.



(b) 5-layer PPLP® model.

Figure 6. Weibull plots of PDIE for different PPLP® systems. a, 3-layer PPLP® system; b, 5-layer PPLP® system.

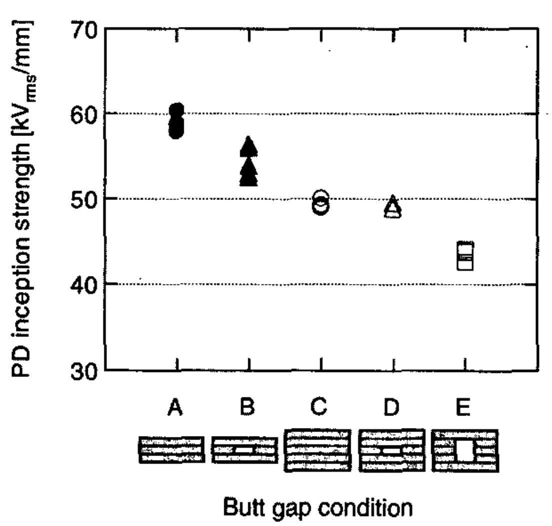


Figure 7. PD inception field strength ($PDIE_{50}$) for different butt gap conditions.

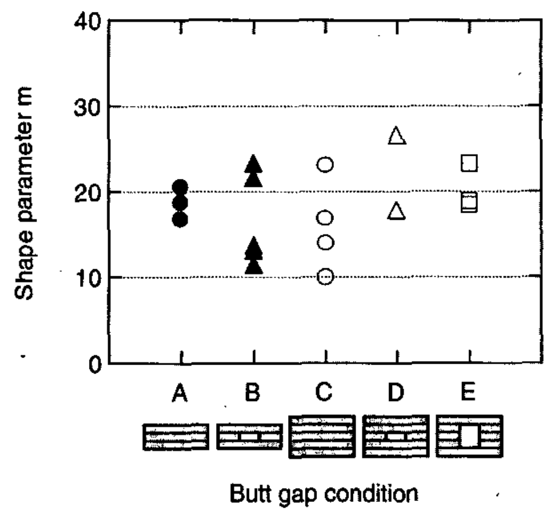


Figure 8. Shape parameter m for different butt gap conditions.

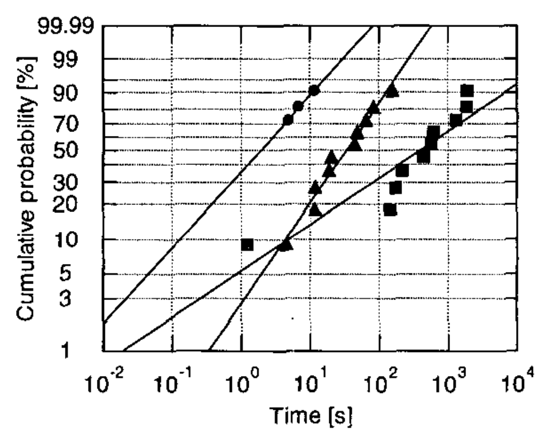


Figure 9. Weibull plots of PD inception time. 3-layer PPLP® system, without a butt gap.

creased, the PD inception time becomes longer. The reason is that as the applied electric field strength decreased, the probability that PD is generated becomes small, and then the PD inception time becomes long.

Next, the V-t characteristics at PD inception for different butt gap condition in the same surface pressure are shown in Figure 11. Figure 11 indicates that the lifetime indices n of the V-t characteristics at PD inception were 111.5 for without butt gap, 88.2 for 0.125 mm butt gap and 86.8 for 0.375 mm butt gap, respectively. Thus the slopes

Table 1. Applied electric field strength (E_{ac}), inclination of Weibull plot (m_t and 50% PD inception time (t_{50}) at 3-layer PPLP® system without butt gap.

	E_{ac} [kV_{rms}/mm]	E_{ac}/E_{50} [%]	m_t	t_{50} [s]
●	61.7	105.0	0.369	1.95
▲	60.2	102.5	0.224	34.09
■	58.8	100.0	0.354	397.07

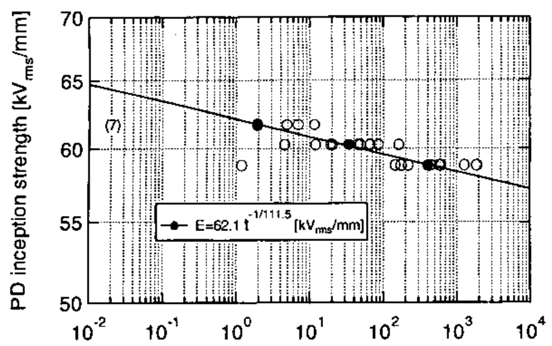


Figure 10. V-t characteristics at PD inception. 3-layer PPLP® system, without a butt gap.

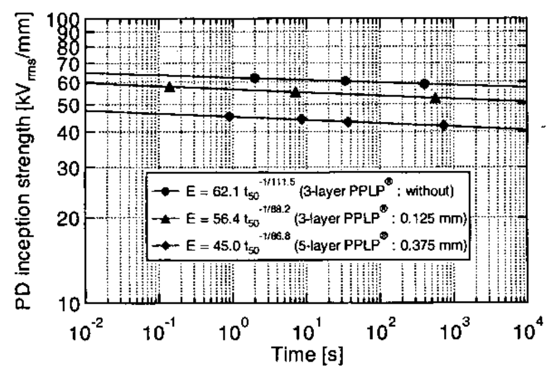


Figure 11. V-t characteristics at PD inception for different butt gap conditions. F = 15.2–15.5 N.

of the V-t characteristics of PD inception are nearly independent of the butt gap condition in the same surface pressure of PPLP.

Furthermore, the V-t characteristics of PD inception for different butt gap conditions are summarized in Table 2. In Table 2, the lifetime indices n of the V-t characteristics of PD inception are about 100 for almost all butt gap conditions in LN_2/PPLP® composite insulation system. The lifetime indices n of the V-t characteristics of PD inception is larger than that of breakdown [7,9,10]. The reason is that at breakdown, the bubbles are produced after PD generation, and then the weak points of the electrical insulation become large.

Table 2. V-t equation for different butt gap conditions.

PPLP® layer	Butt gap thickness [mm]	Surface pressure [N]	V-t equation
3-layer	without	15.2	$E = 62.1\ t^{-1/111.5}$
	0.125 mm	9.4	$E = 52.7\ t^{-1/33.7}$
		15.2	$E = 56.4\ t^{-1/88.2}$
		21.0	$E = 57.7\ t^{-1/108.5}$
5-layer	without	4.9	$E = 53.6\ t^{-1.117.6}$
	0.125 mm	9.7	$E = 50.3\ t^{-1.117.6}$
	0.375 mm	4.9	$E = 42.7\ t^{-1/192.2}$
		9.7	$E = 44.1\ t^{-1/119.7}$
		15.5	$E = 45.0\ t^{-1/86.8}$

6 CONCLUSION

In this paper, we investigated the PD inception and V-t characteristics of PD inception in LN_2/PPLP composite insulation system influenced by butt gap condition. The main results are:

(1) The initial PD is in the range of 2–30 pC and independent of the butt gap condition. Moreover, the PD is larger as PDIE at all butt gap conditions. The reason is that as PDIE is larger, the injected energy which depends on the electric field strength in the butt gap is increased.

(2) The initial PD phase is independent of the butt gap condition. Almost all PDs are generated at the first and third quadrants of the ac voltage phase.

(3) For 3-layer PPLP® the $PDIE_{50}$ for without a butt gap (E_{50} = 59.1 kV_{rms}/mm) is 9% higher than that with 0.125 mm thickness of butt gap (E_{50} = 54.4 kV_{rms}/mm). For 5-layer PPLP® $PDIE_{50}$ without a butt gap (E_{50} = 49.4 kV_{rms}/mm) is almost the same as with 0.125 mm thickness of butt gap (E_{50} = 49.2 kV_{rms}/mm) and higher than that with 0.375 mm thickness of butt gap (E_{50} = 43.5 kV_{rms}/mm) for 5-layer PPLP®. From these results, we can confirm that PD is generated in the butt gap that must be the weak point of the electrical insulation in LN_2/PPLP® composite insulation system.

(4) PDIE for 3-layer (E_{50} = 59.1 kV_{rms}/mm) is 20% higher than that at 5-layer (E_{50} = 49.4 kV_{rms}/mm) without a butt gap. Then PDIE for the 3-layer (E_{50} = 54.4 kV_{rms}/mm) is 10% higher than that for the 5-layer (E_{50} = 49.2 kV_{rms}/mm) with 0.125 mm thickness of a butt gap. Thus, PDIE in a butt gap is dependent on the butt gap condition, especially on the number of PPLP® layers.

(5) Life time indices n of V-t characteristics of PD inception are about 100 for almost all butt gap conditions in LN_2/PPLP® composite insulation system. These values show enough flat characteristics of V-t phenomena of electrical insulation.

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