Electrical Insulation Characteristics at Cryogenic Temperature for High Temperature Superconducting Cables

Hitoshi Okubo* and Naoki Hayakawa**

Abstract - This paper discusses electrical insulation characteristics at cryogenic temperature, especially focusing on partial discharge (PD) inception characteristics, for high temperature superconducting cables. In liquid nitrogen (LN_2) / polypropylene (PP) laminated paper composite insulation system, PD inception strength (PDIE) was evaluated in terms of volume effect and V-t characteristics. Different kinds of butt gap condition were applied in the experiments, using parallel plane and coaxial cylindrical cable samples. Experimental results revealed that the volume effect on PDIE could be evaluated by the statistical stressed liquid volume (SSLV) taking account the discharge probability not only in the butt gap but also in the other thin layers between PP laminated papers. Furthermore, the indices n of V-t characteristics at PD inception were estimated to be 80~110, irrespective of the butt gap condition.

Keywords: butt gap, high temperature superconducting cable, partial discharge, volume effect, V-t characteristics

1. Introduction

High temperature superconducting (HTS) cables have been developed around the world [1]-[3], e.g. 3-phase 66 kV/1 kA HTS cable with the length of 100 m has successfully been developed by TEPCO, SEI and CRIEPI in 2002 [1]. Although the operating voltage of the HTS cables is supposed to be as high as 66kV, 154kV and the higher level, the electrical insulation techniques at cryogenic temperature have not yet been established. Especially, liquid nitrogen (LN_2) / polypropylene (PP) laminated paper composite insulation system is expected to be the most promising system for the cold dielectric type of HTS cables, where butt gaps between the laminated papers have been regarded as the generating points of the partial discharge (PD) leading to the insulation degradation and final breakdown (BD). Therefore, it is necessary to clarify the PD inception characteristics and mechanisms in LN_2/PP laminated paper composite insulation system for the reliable insulation design and testing of HTS cables.

From the above background, we have been investigating the PD inception characteristics in LN_2/PP laminated paper composite insulation system [4], [5]. In this paper, we focused on 2 topics; volume effect on PDIE and V-t characteristics at PD inception. The volume effect was systematized for different electrode and lamination conditions. The n values of V-t characteristics at PD inception were also evaluated for different conditions and compared with those at breakdown.

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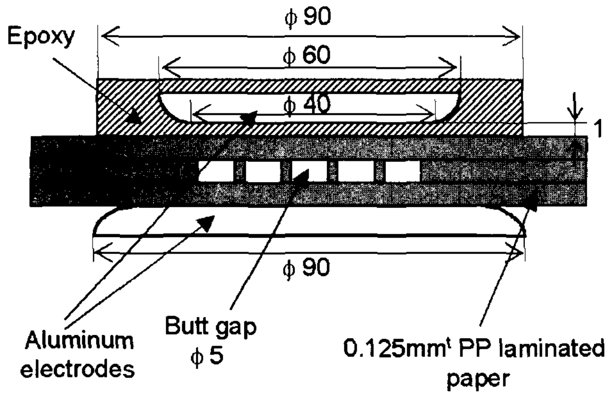
Received: October 23, 2003 ; Accepted: January 5, 2004

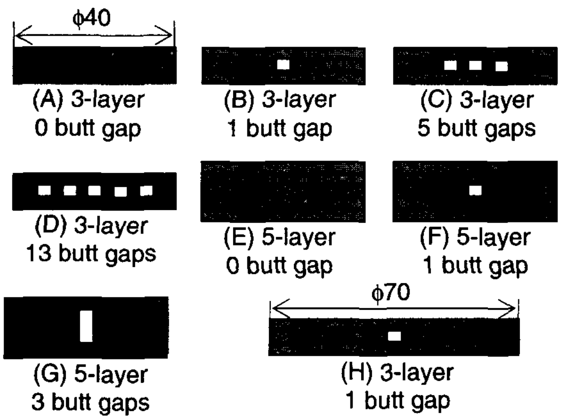
2. Experimental setup

Fig. 1 (a) shows the parallel plane electrode experimental model of LN_2/PP laminated paper composite insulation system for the measurement of volume effect and V-t characteristics. 3 or 5 sheets of PP laminated paper are put between the parallel plane electrodes, where 8 kinds of PP laminated paper and butt gap arrangement are applied as shown in Fig.1 (b). The butt gap configuration in this experiment is circular with 5 mm diameter for different numbers and layers. Upper and lower electrodes are made of aluminum, and the upper electrode is molded with epoxy resin to avoid the edge effect.

On the other hand, Fig. 2 shows the coaxial cable experimental model for the measurement of volume effect of PDIE with the larger volume than the parallel plane model. Three PP laminated paper are put between the inner and outer electrodes with the effective length of 100 mm. The width of butt gap is 1 mm. Furthermore, another electrode configuration as shown in Fig.3 is used for the observation of PD light emission, in order to optically identify the PD location. Two PP laminated papers and one PET sheet are put between the plane electrodes, grounded electrode is the transparent electrode made of glass and ITO film. PD light emission image is observed through an image intensifier and recorded by a high speed video camera.



(a) Parallel plane electrode experimental model



(b) PP laminated paper and butt gap arrangement

Fig. 1 Insulation structure of parallel plane experimental model

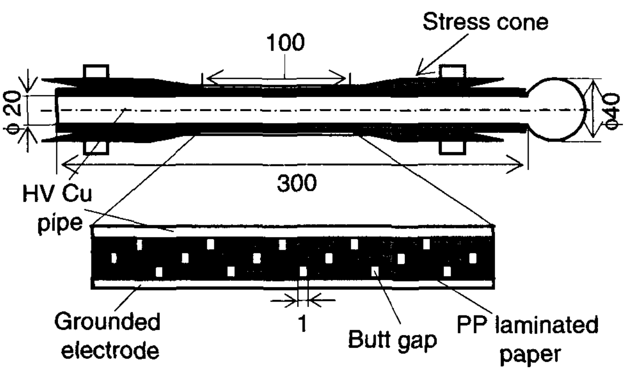


Fig. 2 Cross section of coaxial cable experimental model

Each experimental model was immersed in LN_2 at the atmospheric pressure and stressed under ac high voltage of 60 Hz in a cryostat as shown in Fig. 4. The capacitor bushing was corona free at 100 kV_{rms} in LN_2. PD inception voltage (PDIV) was repeatedly measured for more than 20 times under a fixed condition and converted into PD inception electric field strength (PDIE) in PP laminated paper, using the permittivity of PP laminated paper (ε_r=2.2) and epoxy (ε_r=4.7). $PDIE_{50}$ with the 50% PD inception probability was evaluated by Weibull statistics. The sensitivity of PD detection was lower than 1 pC.

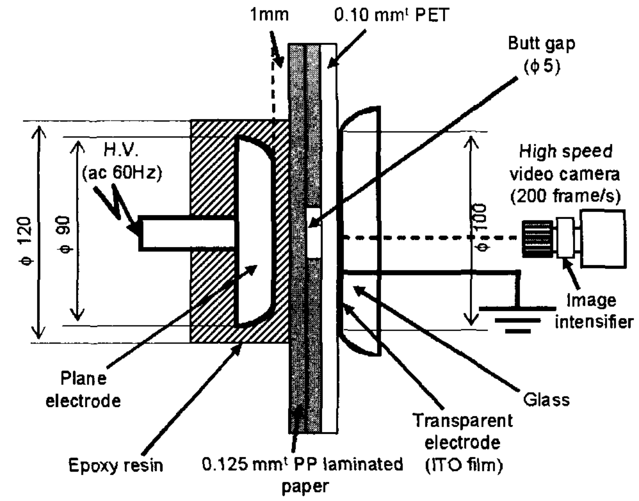


Fig. 3 Electrode configuration for the observation of PD light emission

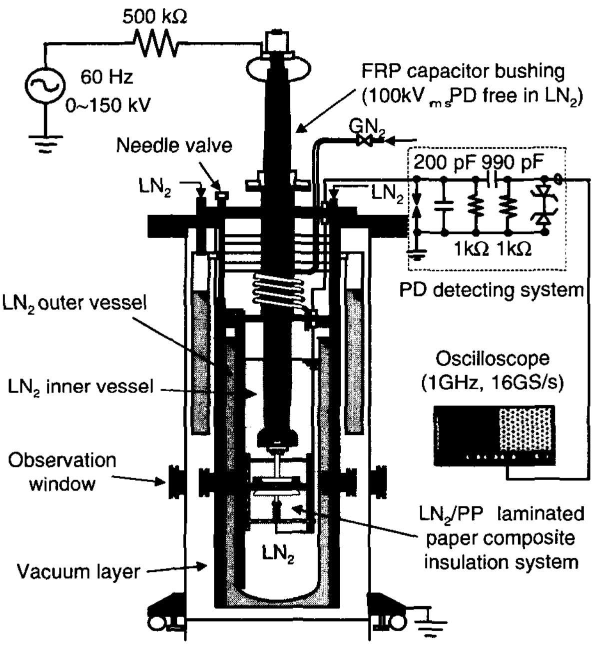
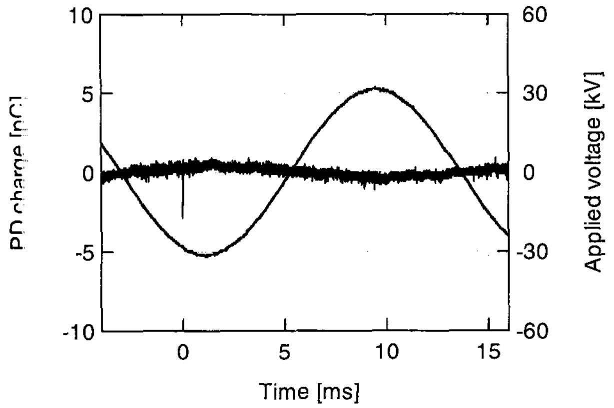


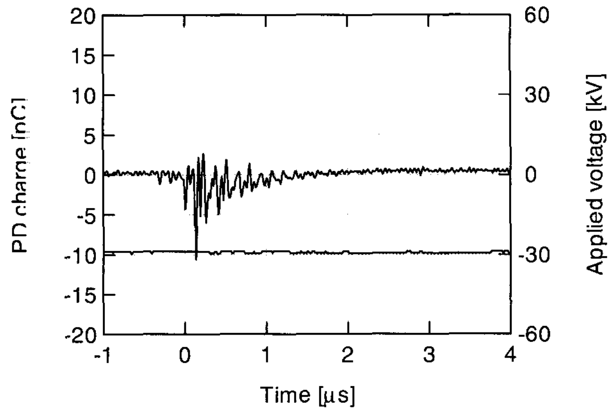
Fig. 4 Experimental setup

3. Volume effect on PD inception strength

Typical PD inception characteristics under the applied voltage of 22 kV_{rms} for the sheet arrangement D are shown in Fig. 5, where the time at the initial PD generation is defined as t=0 ms. The initial PD pulse was detected with the charge magnitude of 3.8 pC at around the peak phase in the negative polarity of the applied voltage. Fig. 6 shows Weibull plots of PDIE for the sheet arrangements A, B, C and D. The Weibull plot gives us $PDIE_{50}$ with 50% cumulative probability in each arrangement. Fig. 7 shows $PDIE_{50}$ as a function of butt gap volume (BGV) for



(a) Phase characteristics of initial PD generation



(b) Initial PD pulse signal

Fig 5 PD inception characteristics for sheet arrangement D

	Sheet arrangement	Number of butt gaps	$PDIE_{50}$ [kV_{rms}/mm]	Shape parameter m
○	A	0	41.2	18.4
△	B	1	38.4	14.7
□	C	5	33.9	13.7
◇	D	13	28.2	12.1

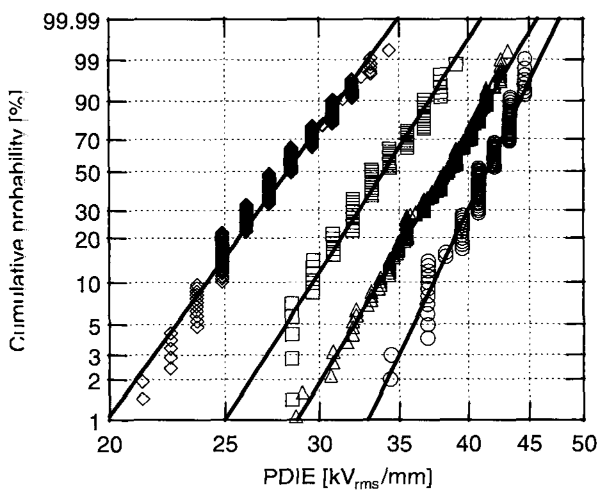


Fig. 6 Weibull plots of PDIE for different sheet arrangements

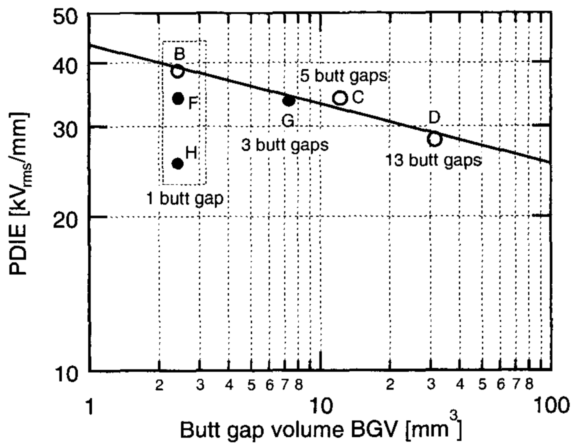


Fig. 7 PDIE as a function of BGV

different parallel plane models in Fig.1. $PDIE_{50}$ decreased with increasing the butt gap number under a fixed condition of the PP laminated paper layer and electrode size (B, C, D in Fig.7), which may suggest the volume effect against BGV. However, $PDIE_{50}$ also decreased with increasing the PP laminated paper layer and the electrode size under a fixed butt gap number (B, F, H in Fig.7), where BGV was constant. These results prove that $PDIE_{50}$ cannot be evaluated only by BGV.

The above results suggest finding the weak points of PD generation other than the butt gaps in LN_2/PP laminated paper composite insulation system. We supposed that there could be LN_2-filled thin areas between laminated layers associated with the surface roughness on PP laminated paper, where the total volume might become large and contribute as weak points enough to induce PD.

Then, we introduced the statistical stressed liquid volume (SSLV), taking account of the measured surface roughness and the discharge probability not only in the butt gap but also in the other thin layers between PP laminated papers. SSLV was expressed by the following equation from Weibull distribution;

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

where E_i is the electric field strength at a volume unit i, E_m is the maximum electric field, m is the Weibull shape parameter for PDIE, $(E_i/E_m)^m$ corresponds to the relative PD probability at each unit.

Using equation (1), SSLV for butt gaps and between layers were calculated for different insulation models, and listed in Table 1. SSLV between layers was verified to be larger than that of butt gaps in most cases. Then, $PDIE_{50}$ in Fig.7 was replotted as in Fig.8 as a function of SSLV. $PDIE_{50}$ decreased linearly in log-log scale with increasing

SSLV for different butt gap numbers, PP laminated paper layers and electrode size, which can be regarded as the volume effect on $PDIE_{50}$. In addition, Fig.8 includes the experimental result for the coaxial cable model in Fig.2. $PDIE_{50}$ of the cable model could be plotted on the regression line for the parallel plane model expressed by the following equation;

$$PDIE_{50} = 90.1 \times SSLV^{-1/2.5} \text{ [kV}_{rms}\text{/mm]} \quad (2)$$

These results suggest that the equation (2) can be regarded as a universal expression for the volume effect on $PDIE_{50}$ in LN_2/PP laminated paper composite insulation system.

Table 1 SSLV and shape parameter for different electrode configuration

	Experimental model	Shape parameter m	SSLV for butt gaps [mm³]	SSLV between layers [mm³]	Total SSLV [mm³]
A	ϕ40 3-layer 0 butt gap	18.4	0	7.54	7.54
B	3-layer 1 butt gap	14.7	0.9	7.42	8.32
C	3-layer 5 butt gaps	13.7	4.84	6.95	11.79
D	3-layer 13 butt gaps	12.1	14.08	6.01	20.09
E	5-layer 0 butt gap	13.9	0	12.57	12.57
F	5-layer 1 butt gap	17.8	1.02	12.37	13.39
G	5-layer 3 butt gaps	21.4	0.25	12.37	12.62
H	ϕ70 3-layer 1 butt gap	12.2	1.08	22.89	23.97
	100 3-layer coaxial cable	12.3	11.94	37.55	49.49

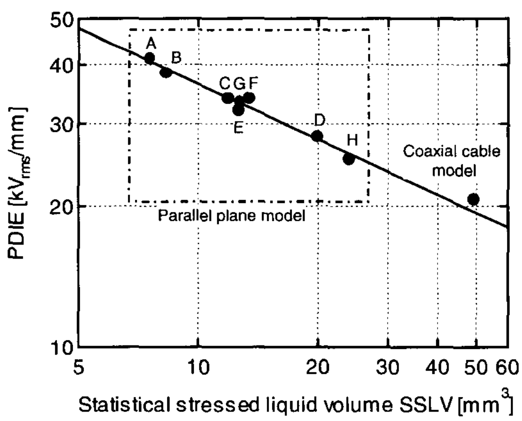
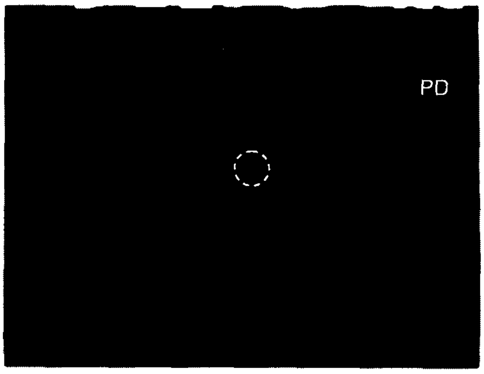


Fig. 8 PDIE as a function of SSLV



Butt gap (ϕ=5mm)

Fig. 9 PD inception light emission at PP laminated layer

In order to verify the PD inception between PP laminated layers, we observed PD light emission image using the transparent electrode model shown in Fig.3. Fig. 9 shows the PD inception light emission observed at the outside of the butt gap, i.e. at between PP laminated paper layers. In most cases, PD inception light emission was detected at the outside of the butt gap. This result supports that the concept of SSLV taking account of the discharge probability at PP laminated papers was applicable to evaluate the volume effect on $PDIE_{50}$ for HTS cable.

4. V-t characteristics at PD inception

V-t characteristics at PD inception for parallel plane experimental models (A), (B) and (G) in Fig.1 (b) are shown in Fig.10. Fig. 10 indicates that indices n of V-t characteristics at PD inception were 80~110, irrespective of the butt gap condition. The n values for different parallel plane models and the surface pressure on PP laminated paper are summarized in Table 2. Table 2 indicates that the n values were higher than 80 in most cases of butt gap condition and surface pressure on PP laminated paper. The difference in the magnitude of the approximated V-t equations can be understood by the volume effect with SSLV.

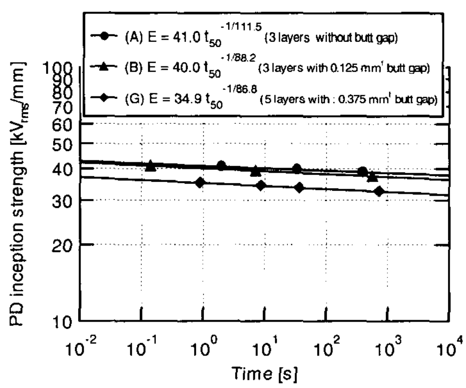


Fig. 10 V-t characteristics at PD inception for different butt gap condition

Table 2 Approximate V-t equation for different butt gap condition

Experimental model		SSLV [mm^3]	Surface pressure [N]	Approximated V-t equation
A	φ40, 3-layer 0 butt gap	7.54	15.2	$E=41.0\,t^{-1/111.5}$
B	φ40, 3-layer 1 butt gap	8.32	9.4	$E=37.4\,t^{-1/33.7}$
			15.2	$E=40.0\,t^{-1/88.2}$
			21.0	$E=40.9\,t^{-1/108.5}$
D	φ40, 3-layer 13 butt gap	20.09	4.9	$E=29.7\,t^{-1/68.4}$
E	φ40, 5-layer 0 butt gap	12.57	4.9	$E=35.3\,t^{-1/117.6}$
F	φ40, 5-layer 1 butt gap	13.39	9.7	$E=35.1\,t^{-1/117.6}$
G	φ40, 5 layer 3 butt gaps	12.61	4.9	$E=32.6\,t^{-1/192.2}$
			9.7	$E=34.2\,t^{-1/119.7}$
			15.5	$E=34.9\,t^{-1/86.8}$
H	φ70, 3-layer 1 butt gap	23.97	4.9	$E=24.1\,t^{-1/150.1}$

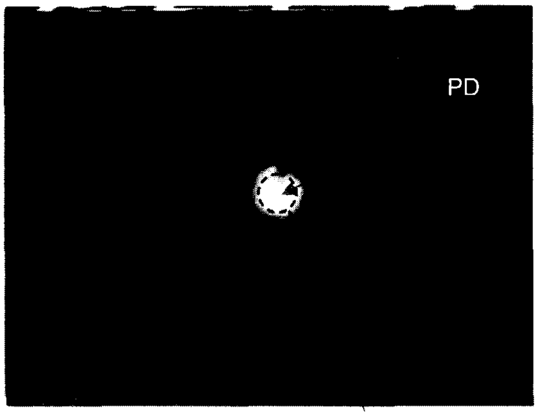


Fig. 11 PD light emission image after PD inception

The n values of V-t characteristics were compared between at PD inception and at BD, where n (n=15~89) at BD [6]-[8] was lower than n at PD inception (n=68~192) in most cases in Table 2. The difference in the n values may be attributed to the difference in the discharge mechanism. PD inception could occur mainly in the thin layers between PP laminated papers rather than in the butt gap, as was verified in previous section by the observation of PD light image. On the other hand, BD would occur via the butt gap filled with bubbles, which was suggested by the fact that another bright PD light emission was observed in the butt gap after the PD inception, as shown in Fig.11. Thus, the lower n values at BD can be interpreted by the following discharge mechanism; PD in the butt gap generated bubbles with the dielectric strength lower than LN_2, which could accelerate the PD development in the butt gap and easily result in BD.

5. Conclusion

We investigated the volume effect and the V-t characteristics both at PD inception in LN_2/PP laminated paper composite insulation system for HTS cables. The main results are summarized as follows;

1. Statistical stressed liquid volume (SSLV) was introduced to evaluate the volume effect, taking account the discharge probability not only in the butt gap but also in the other thin layers between PP laminated papers.
2. $PDIE_{50}$ decreased linearly in log-log scale with increasing SSLV for different butt gap numbers, PP laminated paper layers and electrode size, which could be regarded as the volume effect on $PDIE_{50}$.
3. The n values of V-t characteristics were 80~110 for different butt gap condition and surface pressure on PP laminated paper. The difference in the n values between at PD inception and at BD is attributed to the difference in the discharge mechanism.

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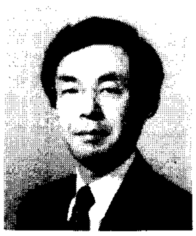

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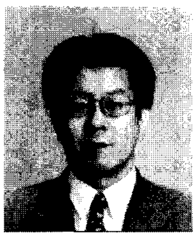

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