Dielectric Characteristics of HTS Cables Based on Partial Discharge Measurement

N. Hayakawa, M. Nagino, H. Kojima, M. Goto, T. Takahashi, K. Yasuda, and H. Okubo

***Abstract*—We have discussed dielectric characteristics of liquid nitrogen (LN_2)/polypropylene (PP) laminated paper composite insulation system for the practical electrical insulation design of high temperature superconducting (HTS) cables. Focusing on the partial discharge (PD) inception characteristics and mechanism, the volume effect and its saturation on PD inception electric field strength (PDIE) was evaluated at atmospheric and pressurized condition. PD inception characteristics under lightning impulse voltage application were also investigated using an electrical and optical PD measuring system, and compared with those under ac voltage application.**

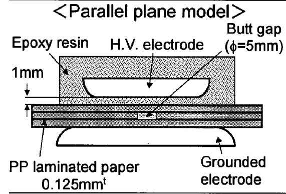
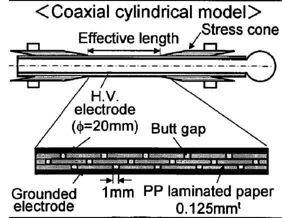
***Index Terms*—High temperature superconducting cable, partial discharge, statistical stressed liquid volume, volume effect.**

I. Introduction

HIGH TEMPERATURE superconducting (HTS) cables have been expected for the higher power density and the lower losses than conventional cables [1]. For example, a 77 kV HTS cable with the length of as long as 500 m is being installed and tested in Japan [2]. However, the electrical insulation design and test schemes of HTS cables have not yet been established. Although, fundamental data on electrical insulation in liquid nitrogen have been mainly obtained [3], [4], dielectric data applicable to the practical insulation design of the HTS cables have not been sufficient. Especially, partial discharge (PD) inception characteristics are crucial to be understood in order to prevent the insulation degradation leading to breakdown. In addition, PD inception electric field strength (PDIE) under both ac and lightning impulse voltage applications should be evaluated for the practical electrical insulation design of HTS cables.

From the above background, we have been investigating the PD inception characteristics and mechanisms of electrical insulation system for HTS cables [5], [6]. We have already evaluated the reduction characteristics of ac PDIE at the larger stressed volume, i.e. "volume effect" on PDIE, in LN_2/polypropylene (PP) laminated paper composite insulation system at atmospheric condition [5]. In this paper, the evaluation of volume effect was extended to both the larger volume region and the higher pressure. Furthermore, PD inception characteristics and mechanisms under lightning impulse voltage application were obtained, discussed and compared with those under ac voltage application.

TABLE I
ELECTRODE CONFIGURATION FOR LN_2/PP LAMINATED PAPER COMPOSITE INSULATION SYSTEM

Configuration	Size	Number of PP laminated paper and butt gap	Shape parameter m	SSLV [mm³]
<Parallel plane model> 	Upper electrode diameter [mm] ϕ40,ϕ70	Number of PP laminated paper 3,5 Number of butt gap 0,1,5,13	12.1 ~ 21.4	5 ~ 30
<Coaxial cylindrical model> 	Effective length [mm] 100,120, 150,1000	Number of PP laminated paper 3,8,16,24,32,48	18.6 ~ 30.2	30 ~ 500

II. Volume Effect on PD Inception Electric Field Strength

A. Experimental Setup

Table I shows the electrode configuration. The parallel plane model consists of two plane electrodes and PP laminated paper layers. The thickness of PP laminated paper layer is 125 μm. In the parallel plane model, we measured PDIE for different numbers of PP laminated paper layers, butt gaps and electrode diameters. The coaxial cylindrical model consists of high voltage copper pipe as an inner cylinder, PP laminated paper layers, and grounded electrode as an outer sheath. In the coaxial cylindrical model, we measured PDIE for different numbers of PP laminated paper layers and effective lengths.

Fig. 1 shows the experimental setup for the measurement of PD inception characteristics. Either parallel plane model or coaxial cylindrical model was immersed in LN_2 at the pressure of 0.1–0.2 MPa. For the measurement of PDIE, we applied ac 60 Hz high voltage more than ten times. PDIE in the parallel plane model was defined as the electric field strength at PD inception in PP laminated paper layer, whereas PDIE in the

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N. Hayakawa and M. Nagino are with the Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya 464-8603, Japan (e-mail: nhayakaw@nuee.nagoya-u.ac.jp; nagino@okubo.nuee.nagoya-u.ac.jp).

H. Kojima, M. Goto, and H. Okubo are with the EcoTopia Science Institute, Nagoya University, Nagoya 464-8603, Japan (e-mail: h-kojima@esi.nagoya-u.ac.jp; goto@esi.nagoya-u.ac.jp; okubo@nuee.nagoya-u.ac.jp).

T. Takahashi is with the Central Research Institute of Electrical Power Industry, Yokosuka 240-0196, Japan (e-mail: tosihiro@criepi.denken.or.jp).

K. Yasuda is with the Super-GM, 5-14-10, Osaka 530-0047, Japan (e-mail: super-gm@nifty.com).

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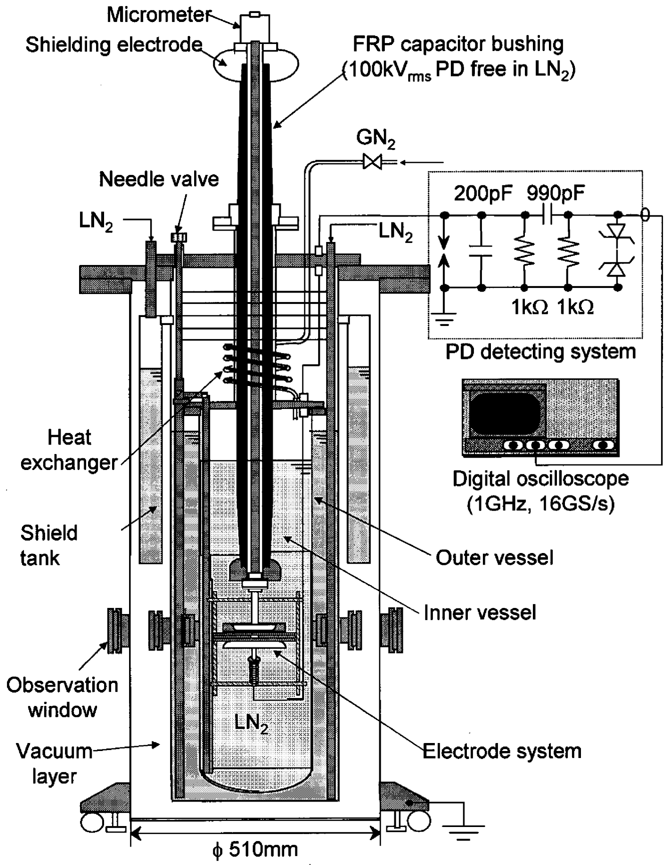

Fig. 1. Experimental setup for PD measurement under ac voltage application.

coaxial cylindrical model was that in the innermost PP laminated paper layer.

In order to discuss the PD inception characteristics and mechanisms of LN_2/PP laminated paper composite insulation system, a new parameter, statistical stressed liquid volume (SSLV), has been introduced [5]. SSLV is the parameter taking account of the discharge probability based on the electric field distribution, not only in the butt gap but also in LN_2-impregnated thin layers to be highly stressed between PP laminated paper layers caused by its own surface roughness. SSLV can be calculated by

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

where E_i is the electric field strength at a volume unit i, E_m is the maximum electric field strength, and m is the Weibull shape parameter for PDIE, $(E_i/E_m)^m$ corresponds to the relative PD probability at the volume unit i. In the calculation procedure of SSLV, not only the butt gap volume but also the volume between PP laminated paper layers were considered. We have discussed the volume effect for SSLV smaller than 50 mm^3 [5], then in this paper, SSLV was extended up to 500 mm^3.

B. Results and Discussions

Fig. 2 shows PDIE as a function of SSLV under atmospheric pressure. Each point in Fig. 2 was calculated statistically with the data from [5], [7]. PDIE decreased linearly on log-log plot with the increase in SSLV at $SSLV < 100\ mm^3$ (volume effect).

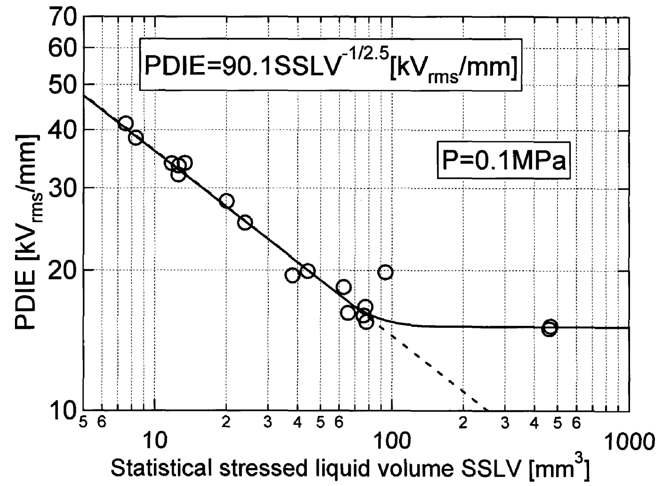

Fig. 2. PDIE as a function of SSLV at $P = 0.1\ MPa$.

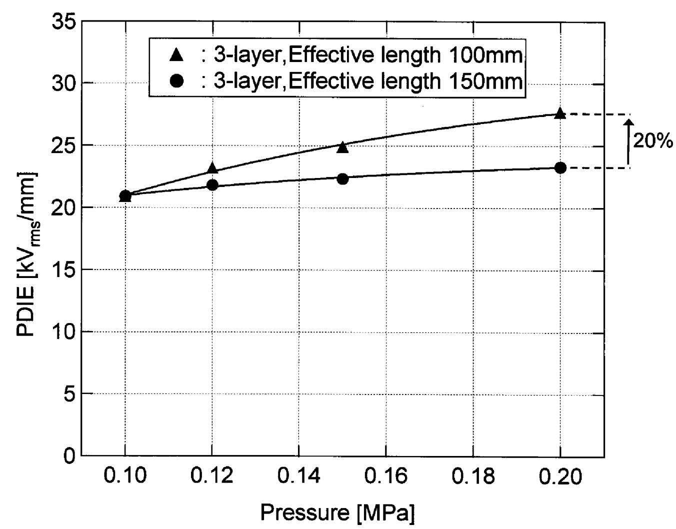

Fig. 3. PDIE as a function of LN_2 pressure for 3-layer coaxial cylindrical models with different effective length.

On the other hand, at $SSLV > 100\ mm^3$, PDIE was almost constant, while suggested that the volume effect on PDIE was saturated at 0.1 MPa and $SSLV > 100\ mm^3$.

Next, PDIE as a function of LN_2 pressure is shown in Fig. 3 for 3-layer coaxial cylindrical model with effective length of 100 mm and 150 mm. There was no difference in PDIE at 0.1 MPa between 100 mm and 150 mm models. On the other hand, at 0.2 MPa PDIE of 100 mm model was higher than PDIE of 150 mm model by 20%. This result means that the volume effect was not yet been saturated at 0.2 MPa, and PDIE of 150 mm model with SSLV larger than that of 100 mm model would further decrease.

Fig. 4 shows PDIE as a function of SSLV for different LN_2 pressures. This figure tells us that the volume effect on PDIE at the smaller SSLV and its saturation at the larger SSLV could appear even at 0.2 MPa. This result verifies that the concept of SSLV could also be applied to the pressurized condition for the evaluation of PD inception characteristics, in other words, PD would be generated not only in the butt gap but also between PP laminated paper layers. The regression curve on PDIE at 0.2 MPa was shifted upward by 13∼40% from that at 0.1 MPa.

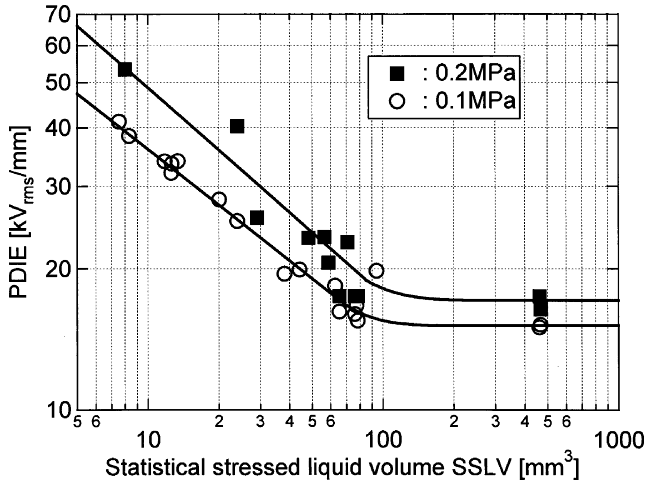

Fig. 4. PDIE as a function of SSLV for different LN_2 pressures.

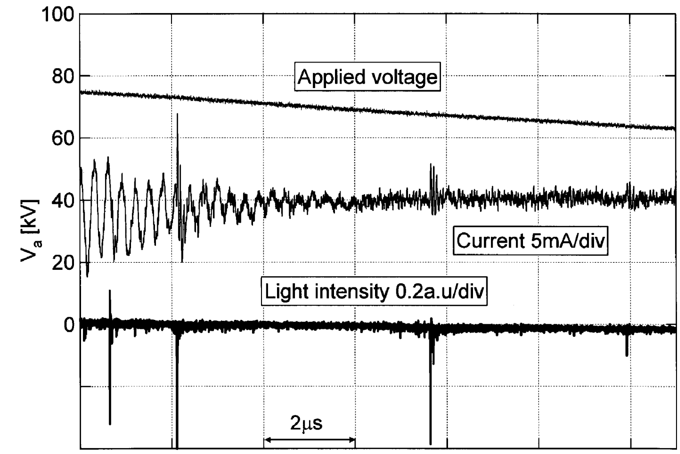

Fig. 6. Applied voltage, PD current and light intensity waveforms under impulse voltage application ($V_a = 82.4\ kV_{peak}$).

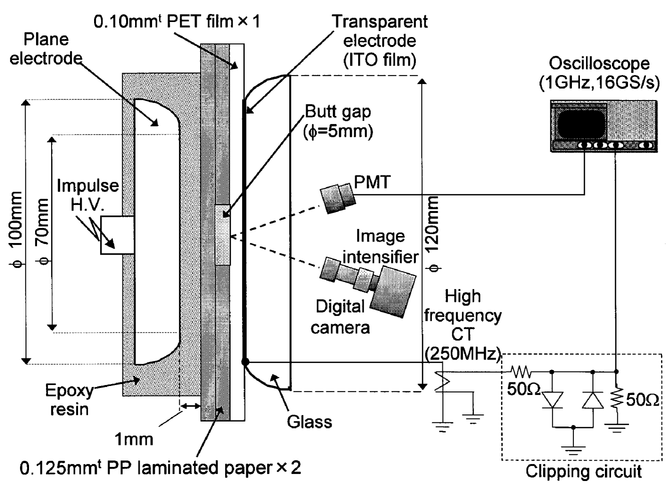

Fig. 5. Experimental setup for optical PD measurement under impulse voltage application.

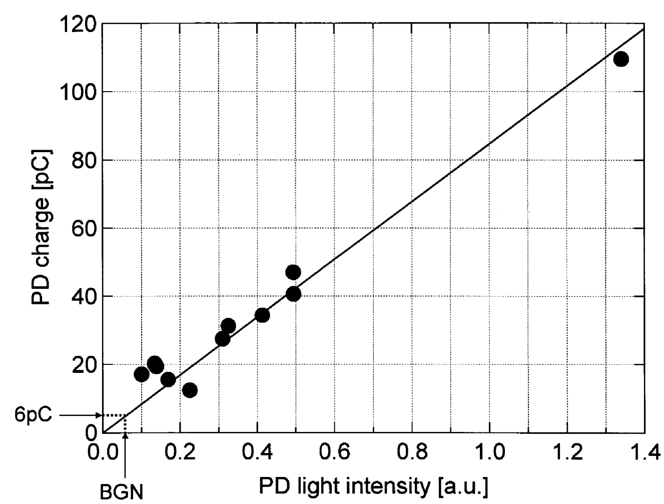

Fig. 7. Relationship between PD charge and PD light intensity under impulse voltage application.

The saturated PDIE at 0.1 MPa and 0.2 MPa were about 15 kV_{rms}/mm and 17 kV_{rms}/mm, respectively. These values will be useful for the practical electrical insulation design of HTS cables.

III. PD Inception Characteristics Under Lightning Impulse Voltage Application

A. Experimental Setup

Fig. 5 shows experimental setup for optical PD measurement under lightning impulse voltage application. Two PP laminated paper layers with a butt gap and one polyethylene terephthalate (PET) sheet were sandwiched between parallel plane electrodes. Grounded electrode was the transparent electrode made of glass and Indium-Tin Oxide (ITO) film. This electrode system was immersed in LN_2, and positive standard lightning impulse voltage (1.2/50 μs) was applied.

We measured PD light intensity and PD current pulse waveforms for PD detection. The PD light intensity pulse was measured by a photo multiplier tube (PMT) through the PET sheet, transparent electrode and observation window in Fig. 1. The PD current pulse was measured by a high-frequency current transformer and a clipping circuit. Moreover, PD light emission image was observed using an image intensifier and a digital camera. PD inception voltage (PDIV) under impulse voltage application was measured by up-down method [8], [9].

B. Results and Discussions

Fig. 6 shows an example of PD light intensity and PD current pulse waveforms at the applied impulse voltage $V_a = 82.4\ kV_{peak}$. This figure tells us that PD light intensity pulses corresponded to PD current pulses. Fig. 7 shows the relationship between PD charge and peak value of the PD light intensity. PD charge was calculated by integrating the corresponding PD current pulse waveform. A good correlation between PD charge and PD light intensity could be seen, and the threshold level of PD detection under lightning impulse voltage application could be regarded as low as 6 pC with considering background noise (BGN) level of 0.06 a.u. for the PMT signal. PDIV under lightning impulse voltage application was evaluated to be 50.6 kV_{peak}.

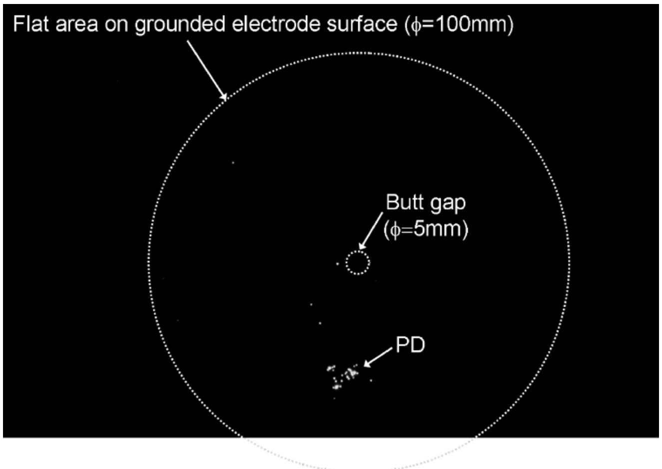

Fig. 8. PD light emission image under impulse voltage application.

PDIV under ac voltage application for the same electrode system was 24.8 $\mathrm{kV_{rms}}$ (35.1 $\mathrm{kV_{peak}}$), under the PD detection level of 2 pC by CR impedance method. Thus, the impulse PDIV was 1.4 times higher than the ac PDIV for the electrode system in Fig. 5.

Fig. 8 shows the PD light emission image during the optical gate width of 10 μs after the impulse voltage application. The light emission was observed outside the butt gap, i.e. between laminated paper layers, also not at the electrode edge. This result suggests the possibility of PD generation between laminated paper layers not only under ac voltage application [5] but also under lightning impulse voltage application, where SSLV between laminated paper layers is larger than SSLV in the butt gap.

IV. CONCLUSION

In this paper, we discussed PD inception characteristics of $\mathrm{LN_2/PP}$ laminated paper composite insulation system for the practical electrical insulation design of HTS cables. The main results are listed as follows:

1. Under ac voltage application, PDIE at 0.1 MPa decreased linearly on log-log plot with the increase in SSLV (volume effect) at $\mathrm{SSLV} < 100\ \mathrm{mm}^3$. On the other hand, PDIE became almost constant at $\mathrm{SSLV} > 100\ \mathrm{mm}^3$, i.e. the volume effect on PDIE was saturated.
2. Under pressurized condition up to 0.2 MPa, the volume effect on PDIE at the smaller SSLV and its saturation at the larger SSLV could also be verified. PDIE at 0.2 MPa was 13∼40% higher than that at 0.1 MPa, and he saturated PDIE at 0.1 MPa and 0.2 MPa were about 15 $\mathrm{kV_{rms}/mm}$ and 17 $\mathrm{kV_{rms}/mm}$, respectively.
3. Under lightning impulse voltage application, the optical PD measurement enabled us to detect PD signal as low as 6 pC. We measured PD light intensity pulse and PD current pulse. The impulse PDIV was 1.4 times higher than the ac PDIV. The impulse PD light emission image was observed between laminated paper layers with SSLV larger than that in the butt gap.

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