# Impulse and ac PD Inception Characteristics of $LN_2$/Polypropylene Laminated Paper Composite Insulation System

H. Okubo[1], M.Nagino[1], H.Kojima[1], N.Hayakawa[1], T.Takahashi[2] and K.Yasuda[3]
[1]Nagoya University, Nagoya, JAPAN
[2]Central Research Institute of Electrical Power Industry, Yokosuka, JAPAN
[3]Super-GM, Osaka, JAPAN

*Abstract:* **We discussed partial discharge (PD) inception characteristics of liquid nitrogen ($LN_2$) / polypropylene (PP) laminated paper composite insulation system for high temperature superconducting (HTS) cables. In this paper, we measured PD inception characteristics under lightning impulse voltage application by both electrical and optical methods. The impulse PD inception characteristics were compared with those under ac voltage application, and the PD generation mechanisms were discussed. Experimental results revealed that PD detection sensitivity under lightning impulse voltage application reached as small as 6 pC. PD was verified to be generated not only inside the butt gap but also outside the butt gap under both lightning impulse and ac voltage applications. AE sensors could also be applied to PD measurement under ac voltage application.**

## INTRODUCTION

Applications of superconducting technology to power apparatus have been developed around the world. Especially high temperature superconducting (HTS) cables are expected to have the higher power density and the lower losses than conventional power cables [1, 2]. The electrical insulation system for HTS cables consists of liquid nitrogen ($LN_2$) / polypropylene (PP) laminated paper composite insulation system. However, the electrical insulation characteristics of $LN_2$/PP laminated paper composite insulation system have not yet been clarified in detail. Especially, partial discharge (PD) inception characteristics and mechanisms under impulse and ac voltage applications are crucial to be understood in order to prevent the insulation degradation leading to breakdown.

From the above background, we have been investigating the PD inception characteristics of $LN_2$/PP laminated paper composite insulation system. We have already evaluated the volume effect of ac PDIE at atmospheric and pressurized conditions [3, 4]. In this paper, we developed a novel technique for PD measurement under lightning impulse voltage application, by using electrical and optical methods, and applied to the PD inception measurement for $LN_2$/PP laminated paper composite insulation system. Experimental results were compared with those under ac voltage application, and their physical mechanisms were discussed.

## IMPULSE PD MEASUREMENT BY ELECTRICAL AND OPTICAL METHODS

### Experimental setup

Figure 1 shows the electrode system for electrical and optical PD measurement under lightning impulse voltage application. Two PP laminated papers (thickness: 0.125 mm) with a butt gap (diameter: 5 mm) and one polyethylene terephthalate (PET) sheet (thickness: 0.10 mm) were inserted between parallel plane electrodes. Grounded electrode was the transparent electrode made of glass and ITO (Indium-Tin Oxide) film. This electrode system was immersed in $LN_2$ at atmospheric condition and positive standard lightning impulse voltage (1.2/50μs) was applied.

We measured PD light intensity and PD current pulse waveforms simultaneously for PD detection. The PD light intensity pulse was measured by a photo multiplier tube (PMT) through the PET sheet, transparent electrode. The PD current pulse was measured by a high-frequency current transformer (CT) 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.

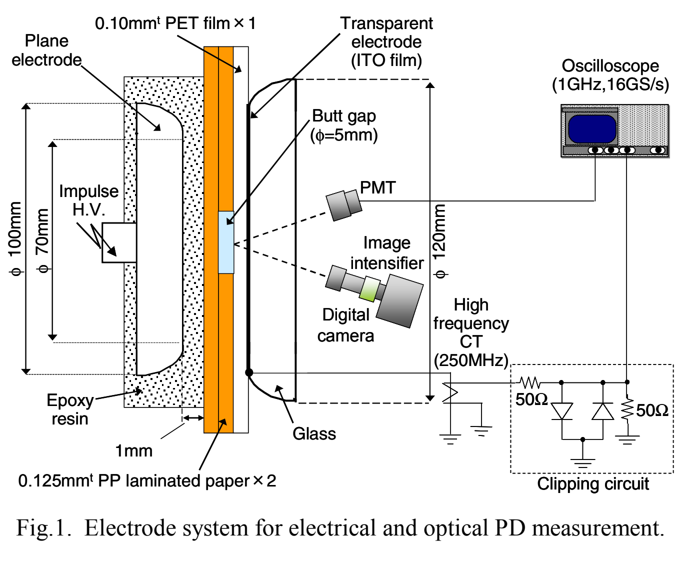



Fig.1. Electrode system for electrical and optical PD measurement.

## Results and discussions

Figure 2 shows PD current pulse and PD light intensity waveforms at the applied voltage (a) $V_a$=74.6 $kV_{peak}$ (94.8 $kV_{peak}$/mm) and (b) $V_a$=82.4 $kV_{peak}$ (104.7 $kV_{peak}$/mm), respectively, where the electric field strength represents the value at PP laminated paper layer. Figure 2 tells us that PD light intensity pulses correspond to PD current pulses. We calculated PD charge from PD current pulse waveform, and compared it with peak value of the corresponding PD light intensity pulse as shown in Fig. 3. PD charge increased linearly with the increase in the PD light intensity, and the threshold level of PD detection considering background noise (BGN) level of 0.06a.u could be regarded as small as 6 pC under impulse voltage application. The 50% PD inception electric field strength ($PDIE_{50}$) was 63.9 $kV_{peak}$/mm under such PD detection sensitivity. $PDIE_{50}$ under ac voltage application for the same electrode configuration using CR impedance circuit, which had PD detection sensitivity of 2 pC, was 31.5 kV $_{rms}$/mm. Thus, the impulse $PDIE_{50}$ was about 1.4 times higher than ac $PDIE_{50}$ for this electrode system.

Figure 4 shows the PD light emission image under impulse voltage application for the optical gate width of 10 μs after the impulse voltage application. PD location in Fig. 4 (a) was inside the butt gap, whereas that in Fig. 4 (b) was clearly outside the butt gap. In the case of ac voltage application, PD would be generated not only in the butt gap but also in $LN_2$-impregnated thin layers between each PP laminated paper due to its surface roughness [3]. These results suggest that the PD generation mechanism is also applicable to that under impulse voltage application, and PD was generated more frequently in $LN_2$-impregated thin layers between PP laminated paper layers.

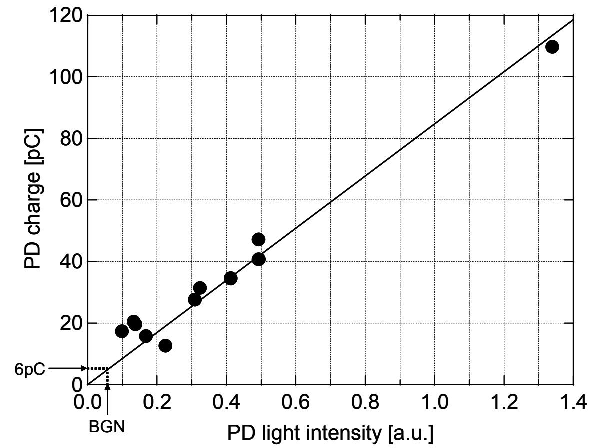
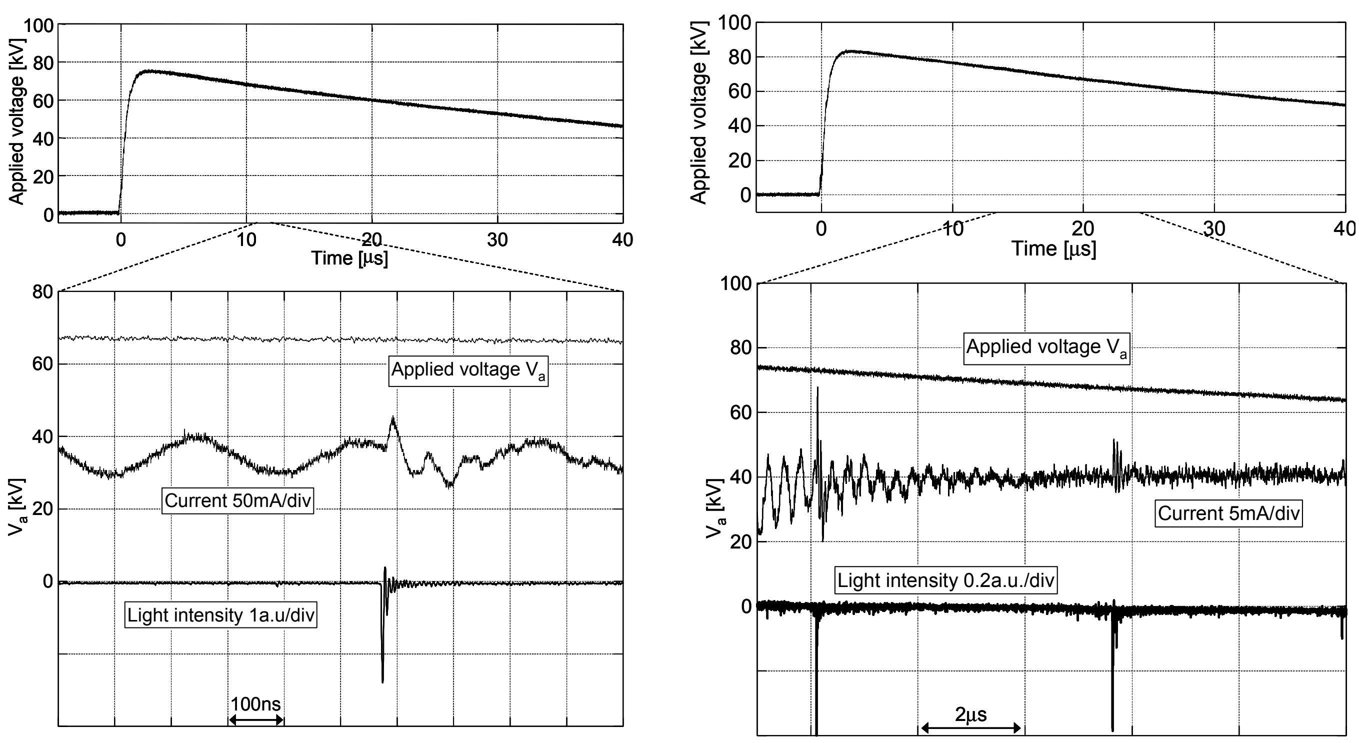


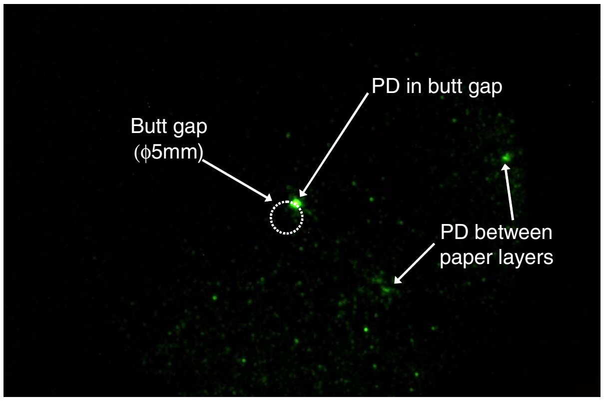

Fig.3. Relationship between PD charge and PD light intensity.



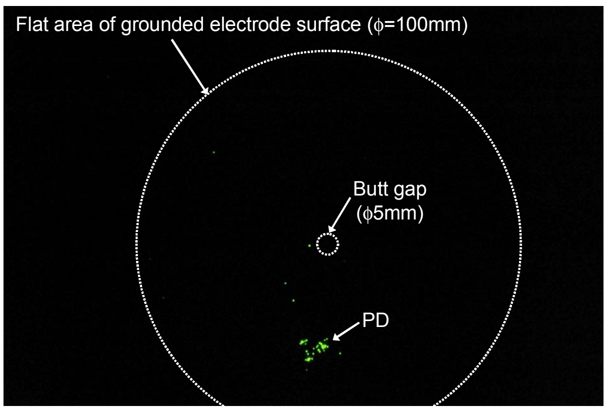

(a) $V_a$=74.6 $kV_{peak}$ (94.8 $kV_{peak}$/mm)

(b) $V_a$=82.4 $kV_{peak}$ (104.7 $kV_{peak}$/mm)

Fig.2. PD current and light intensity waveforms under lightning impulse voltage application.




(a) PD inside butt gap




(b) PD outside butt gap

Fig.4. PD light emission image under impulse voltage application.

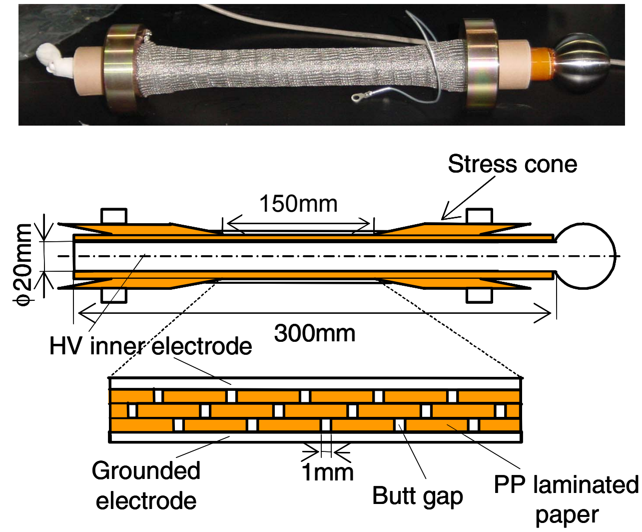



Fig.5. Coaxial cylindrical model (3-layer).

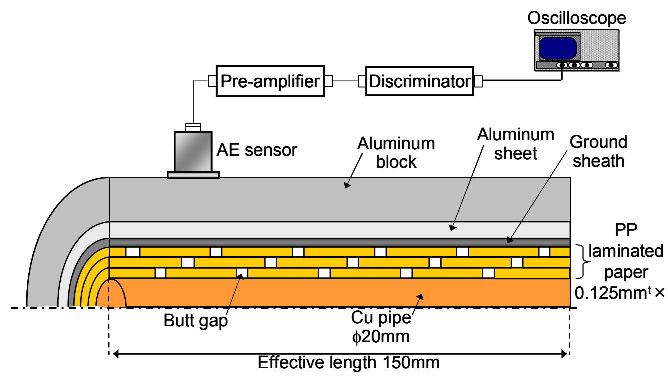



Fig.6. Experimental setup for PD measurement by acoustic method.

## AC PD MEASUREMENT BY ACOUSTIC METHOD WITH AN AE SENSOR

### Experimental setup

Figure 5 shows the electrode configuration of 3-layer coaxial cylindrical model. The coaxial cylindrical model consists of high voltage electrode as an inner cylinder, PP laminated paper layers, and grounded electrode as an outer sheath. The effective length of the model was 150 mm.

Figure 6 shows the experimental setup for PD measurement by acoustic method with an AE sensor. In order to transmit the PD-induced AE signal efficiently, an aluminum block and an aluminum sheet were attached between the coaxial cylindrical model and the AE sensor (resonance frequency 140 kHz). The electrode system was immersed in $LN_2$ at atmospheric condition. The AE signal was measured by an oscilloscope through a pre-amplifier and a discriminator.

### Results and discussions

Figure 7 shows a typical PD-induced AE sensor signal and PD charge under ac voltage application ($V_a$=8.5 $kV_{rms}$). Both PD signals were detected at the positive and negative peaks of the applied voltage waveform. Note that the AE signal was detected with the time delay of about 40 µs after the PD charge signal. If the traveling speed of AE signal in constituent solids is assumed to be 10 times of that in air [5], the time delay of 40 µs can be converted to the length of about 150 mm. Thus, the time delay of 40 µs may be attributed to the traveling time of AE signal associated with the PD in the coaxial cylindrical model.

Next, we discussed investigated the correlation between AE signal and PD charge. We focused on the total PD energy and investigated the relationship between the peak value of AE signal and total PD energy. Total PD energy $J$ was calculated by

$$J = \sum_{i=1}^{n} \frac{q_i V_a}{2} \tag{1}$$

where $q$ is the PD charge measured by CR impedance circuit, $V_a$ is the applied voltage (rms), and n is the number of PD generation corresponding to the AE signal.

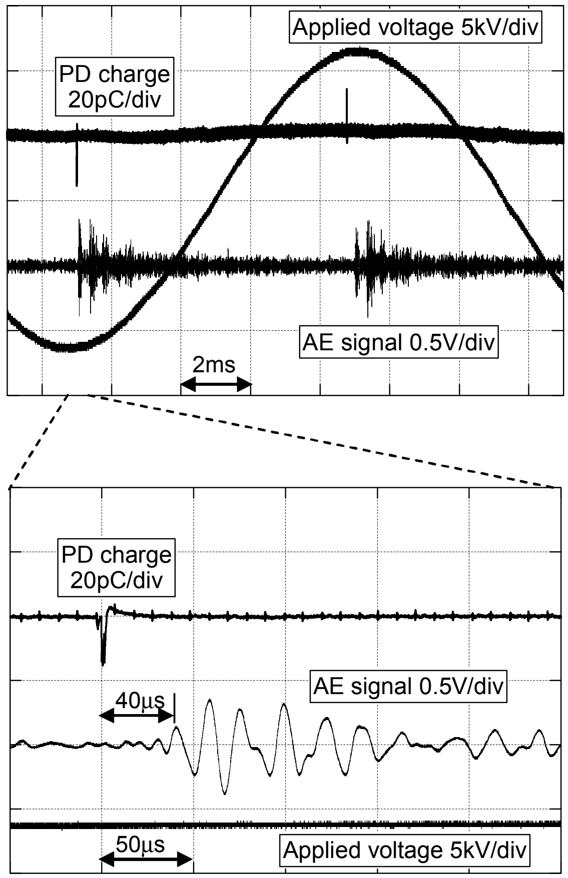



Fig.7. AE signal and PD charge under ac voltage application. ($V_a$=8.5 $kV_{rms}$)

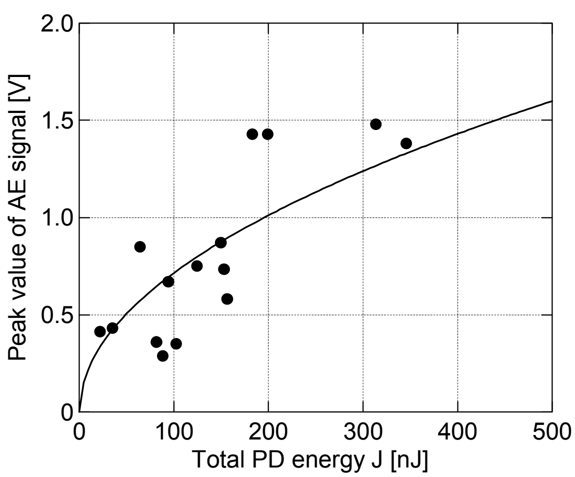



Fig.8. Relationship between peak value of AE signal and total PD charge.

Figure 8 shows the relationship between peak value of AE signal and total PD energy. The peak value of AE signal was proportional to the square root of the total PD energy, which can be interpreted by the fact that the energy of wave is generally proportional to the square of the amplitude of wave [5]. These results suggest that the acoustic method for PD measurement can be applied to $LN_2$/PP laminated paper composite insulation system for HTS cables.

## CONCLUSIONS

We investigated PD inception characteristics and mechanisms of $LN_2$/PP laminated paper composite insulation system for HTS cables under lightning impulse and ac voltage applications. Simultaneous PD measurement of PD current pulse and PD light intensity waveforms enabled us to detect PD signal with the sensitivity as small as 6 pC under lightning impulse voltage application. In addition, acoustic method with AE sensor was verified to be applicable to PD measurement under ac voltage application.


## ACKNOWLEDGMENT

This work has been carried out as a part of Super-ACE (the research and development of fundamental technologies for superconducting AC power equipment) project of METI (the Ministry of Economy, Trade and Industry), as a contract research from NEDO (the New Energy and Industry Technology Development Organization).


## REFERENCES


[1] M. Coevoet and P. Ladie, "Development project on HTS cable", 6th International Conference on Insulated Cables, A.3.4, pp. 95–98, 2003.

[2] K. Ueda, O. Tsukamoto, S. Nagaya, H. Kimura and S. Akita, "R&D of a 500m superconducting cable in Japan", IEEE Trans. on Applied Superconductivity, Vol.13, No.2, pp. 1946–1951, 2003.

[3] N. Hayakawa, T. Kobayashi, M. Hazeyama, T. Takahashi, K. Yasuda and H. Okubo, "Partial discharge inception characteristics of $LN_2$/PP laminated paper composite insulation system for high temperature superconducting cable", IEEE Trans. on Dielectrics and Electrical Insulation, Vol.12, No.1, pp. 166–174, 2005.

[4] N. Hayakawa, M. Nagino, H. Kojima, M. Goto, T. Takahashi, K. Yasuda and H. Okubo, "Dielectric characteristics of HTS cables based on partial discharge measurement", Applied Superconductivity Conference 2004, 1LT04, 2004.

[5] L. E. Lungaard, "Partial discharge – Part XIII: acoustic partial discharge detection – fundamental considerations", IEEE Electrical Insulation Magazine, Vol.8, No.4, pp.25-31. 1992.