

Discrimination of Partial Discharges in Gaseous and Liquid Nitrogen by Using Waveform Characteristics^{*)}

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The cryogenic coolant is important as an electrical insulation in an immersion cooling. One of the dielectric breakdown mechanisms of the cryogenic coolant is via bubbles, caused by partial discharge (PD). The insulation performance has been discussed with PD parameters and breakdown voltage. However, the essential PD mechanism has not been clarified in detail. In this paper, PDs in gaseous and liquid nitrogen were discriminated based on characteristics of the original PD waveform. It was shown that the difference in charge behavior appears significantly in the fall time of the original PD waveform.

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1. Introduction

Superconductivity technology can contribute to lower environment load by CO₂ reduction due to the high efficiency energy supply. Superconducting coils have many applications such as motors for electric aircrafts and ships, transformers, superconducting power storage systems, etc. [1–3]. It is possible to obtain large capacity and high efficiency driving with a considerable reduction in size and weight of coils because of the large current application by the superconducting technology. The superconducting coil is cooled by directly immersing it in a cryogenic coolant or by conduction using a refrigerator etc. For nuclear fusion applications, there is a superconducting coil, which composes a superconducting cable-in-conduit conductor cooling by 4.5 K supercritical helium forced flow [4]. In the direct cooling by immersing a cryogenic coolant, the coolant has two functions: as a cooling and as an electrical insulation. It is necessary to evaluate cooling and electrical insulation properties to maintain the long-term reliability. One of the dielectric breakdown mechanisms of liquids is via bubbles. Particularly in the cryogenic coolants, the vaporization is easy to occur immediately when the energy of partial discharge (PD) is injected to the coolant. As a result, the bubbles (vaporized gases) promote further discharges, which leads to the dielectric breakdown.

In many conventional PD measurements, an original PD waveform is processed with an analog filter composed by an LCR circuit. Then, it is converted into classical

parameters such as PD magnitude or phase angle generation. The electrical insulation performance of the cryogenic coolant has been discussed with these PD parameters and the dielectric breakdown voltage [5–7]. However, the essential PD mechanism in the cryogenic coolant has not been clarified in detail. The original PD waveform shows both processes, namely electro avalanche and ion sweep-out, in the discharge space. In other words, the information related to the charge behavior can be obtained from the difference of the rise time, fall time or frequency spectrum in the original PD waveform. The conventional PD measurement does not include this important information.

Except for special applications, such as nuclear fusion, many superconducting coils cooled by liquid nitrogen have many advantages for utilizing high-temperature superconducting technology. Given the global helium shortage, it is urgent to clarify the electrical insulation performance of liquid nitrogen. In this paper, a measurement system that can acquire original PD waveforms was constructed. The PDs in gaseous and liquid nitrogen were discriminated based on the difference in the feature values compared to the original PD waveform.

2. Measurement Method

2.1 Conventional PD measurement technique and original PD waveform

As conventional oscilloscopes have lower frequency characteristics than the current one, the PD waveform was obtained by that of the original PD waveform: it was intentionally oscillating using a resonance type of detection

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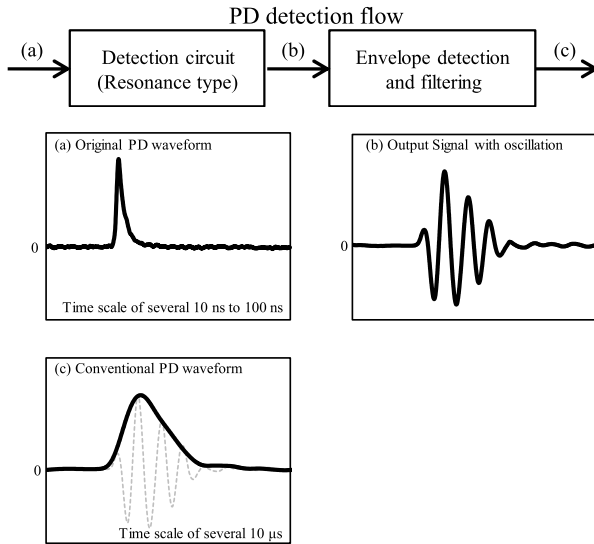


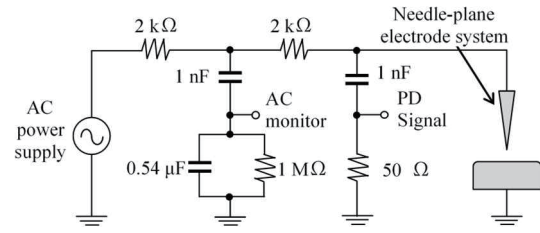
Fig. 1 Schematic diagram of PD detection and PD waveforms.

circuit and the envelope was detected, as shown in Fig. 1. This method is still widely used for on-site measurement. The rise and fall times of the PD waveform are roughly determined by frequency characteristics of the detection circuit. For this reason, the discussion of the PD characteristics based on the charge amount has been mainly performed. However, by designing a detection circuit having sufficient frequency band, a PD waveform with small oscillation, namely the original PD waveform, can be acquired.

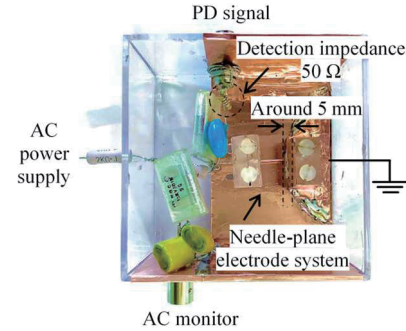
2.2 PD measurement system

Figure 2 shows the measurement system for the original PD waveform. The detection impedance is only resistance, and the matching is performed at $50\ \Omega$. The needle-plane electrode system with gap distance around 5 mm was employed. AC voltage about 3 kVrms was applied to the electrode system. A coupling capacitor of 1 nF and a detection impedance of $50\ \Omega$ were connected in parallel with the electrode system, and about 100 original PD waveforms were acquired along the time series. The PD measurements were performed in gaseous or liquid nitrogen. For the measurement in gaseous nitrogen, the measurement system was installed at about 1 cm height from the level of liquid nitrogen in the thermal insulated container. Gaseous nitrogen (196 K) was generated by vaporization of liquid nitrogen in boiling state. The temperature of gaseous nitrogen was not controlled, but it was confirmed that the temperature around the electrode system did not fluctuate during the experiment.

In addition, the measurement system was completely immersed in liquid nitrogen (77 K) to observe the PDs in it. The rise and fall times were defined as the time difference from 10% to 90% of the maximum amplitude of the PD waveform. In this paper, the analysis was conducted with negative PDs because the number of negative PDs is more dominant than that of positive PDs.



(a) Electrical circuit.



(b) Photo image.

Fig. 2 Measurement system for original PD waveforms.

3. Results and Discussion

3.1 Original PD waveforms and their feature values

Figure 3 shows typical examples of the original PD waveform in gaseous and liquid nitrogen, being observed different feature values of the original PD waveform. There is a significant difference in fall time of original PD waveforms. For example, as shown in Fig. 4, PD characteristics have been discussed by using the charge amount in the conventional measurement. Figure 4 is a box-whisker plot for charge amount of PDs. It was found that the charge amount of gaseous nitrogen is larger than that of liquid nitrogen. However, the rise time/fall time–charge amount distributions (Fig. 5) show more significant changes.

The rise and fall times show the behavior of electrons and ions, respectively. If the PD in gaseous and liquid nitrogen is Townsend type discharge, the full width at half maximum Δt is expressed by equation (1) [8, 9]. The definition of the full width at half maximum is as shown in Fig. 3.

$$\Delta t = d/v = d/\mu E. \quad (1)$$

Here, d , v , μ , E are the gap length in a discharge space, drift velocity, mobility of positive ions and electric field, respectively. In general, the drift velocity of electrons is faster than that of ions. Therefore, it can be considered that the full width at half maximum Δt of the original PD waveform is equivalent to the fall time.

The drift speed of the charges depends on the pressure and temperature of the ambient medium. In our measurement, the gaseous nitrogen at 196 K under atmospheric pressure was employed as a sample, but the bub-

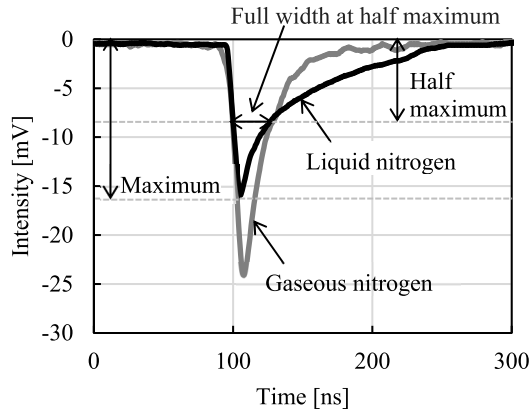


Fig. 3 Original PD waveforms.

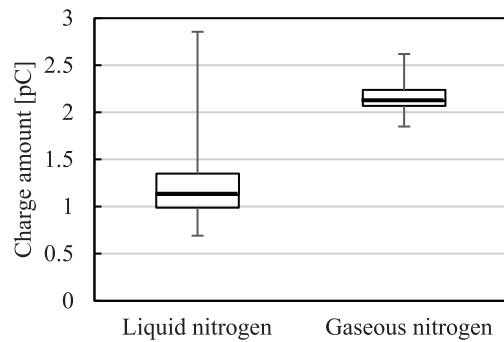
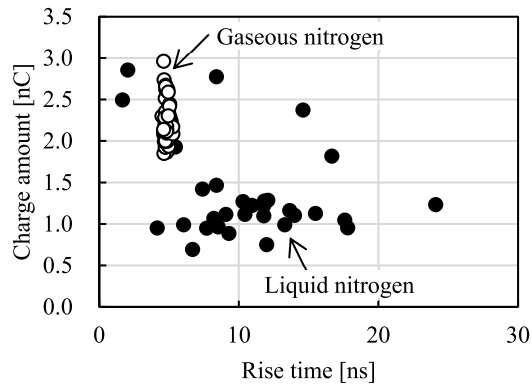
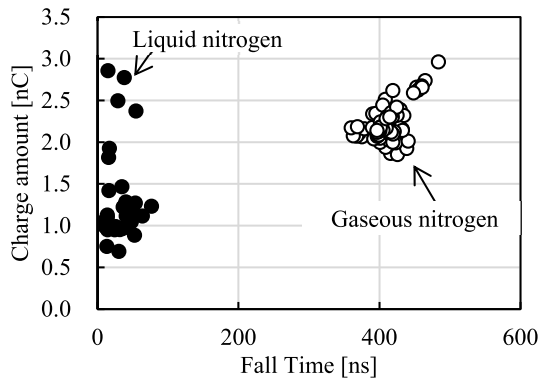


Fig. 4 Charge amount of PDs.



(a) Rise time-charge amount.



(b) Fall time-charge amount.

Fig. 5 Distributions by feature values in original PD waveforms.

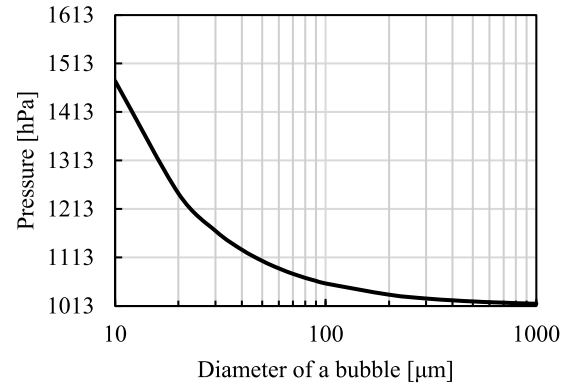


Fig. 6 Bubble size dependence of pressure.

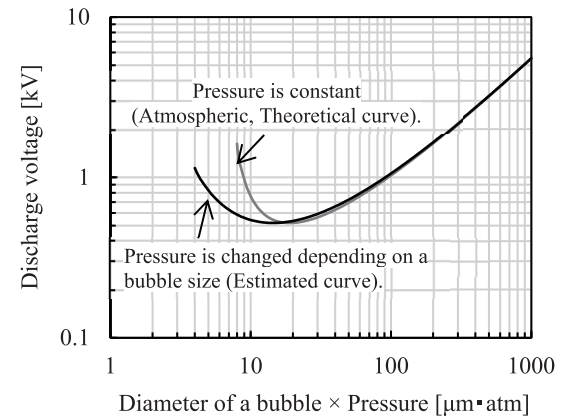


Fig. 7 Estimation of discharge voltage based on pressure increase in a bubble.

ble (gaseous nitrogen) in liquid nitrogen was at 77 K, thus, the inside pressure should be different. The effect of the pressure and temperature on the PD characteristics are discussed as follows.

(a) The effect of the pressure

The inside pressure of a bubble in a liquid usually becomes higher than the atmospheric pressure due to the surface tension. In addition, the inside pressure depends on the bubble size and it can be estimated by Young-Laplace's equation [10]. Figure 6 shows the bubble size dependence of the inside pressure, which was estimated about 1.5 times higher than the atmospheric pressure under the 10 μm bubble. Paschen's curve is an important law for considering the discharge voltage of gases and there are many references on the theoretical formula of this curve [12]. Nitrogen follows this law up to around 78 K [11]. The estimated curve in Fig. 7 was calculated from the theoretical formula of Paschen's curve considering the change of the interior pressure of a bubble. Even considering the pressure change, the discharge voltage was estimated to be almost the same in the range of the bubble size from several hundred μm to several mm, as shown in Fig. 7. Although the behavior of bubbles changes with the voltage application, it has been reported in many experimental re-

sults that bubbles in liquid nitrogen are several hundred μm at the beginning and grow to about several mm [13, 14]. The observed bubbles in our experimental condition also had almost the same size. Therefore, it is unlikely that the pressure change in the bubble affects the change in the PD waveform.

(b) The effect of the temperature

Many experimental results on the drift velocity in gases have been reported [15, 16]. The drift velocity is usually evaluated using the converted electric field E/p , where p is a pressure. Kover *et al.* [16] experimentally showed the temperature dependence of the drift velocity of nitrogen ions. They indicated that the drift velocity has the transition region against the converted electric field E/p . In addition, this velocity becomes almost constant in the transition region, even when the temperature changes from 300 K to 70 K. The converted electric field E/p under our experimental condition was about $0.35 \text{ kV}/(\mu\text{m} \cdot \text{atm})$ using average electric field, which does not match their experimental conditions. However, the order of the drift velocity could not be expected to significantly change based on their results.

From these discussions, it is suggested that the fall time of the original PD waveform in gaseous and liquid nitrogen is still different even considering the temperature and pressure difference.

3.2 Difference in fall time of original PD waveform

The energy that the electrons obtain from the electric field E is given by $eE\lambda$, where e and λ are an elementary charge and a mean free path, respectively. If the energy of the electrons accelerated by the electric field E is converted into the vibration energy of the liquid molecule by collisions, the equation (1) can be rewritten as equation (2) using the mean free path λ [17].

$$\Delta t = de\lambda/\mu h\nu. \quad (2)$$

Here, h and ν are the Planck constant and a vibration frequency of liquid molecule, respectively.

The full width at half maximum Δt is proportional to the mean free path λ . The mean free path λ in gaseous is usually longer than that in liquid and this difference is one of the reasons that the fall time of gaseous nitrogen becomes longer than that of liquid nitrogen.

4. Conclusion

The measurement system was constructed to allow the acquirement of the original PD waveforms along time series. It was shown that it is possible to discriminate between PD in liquid and in gaseous nitrogen by using the feature values of the PD waveform. In the conventional PD measurements, the PD characteristics are mainly analyzed using the charge amount of PD and phase angle of PD generation. Comparing charge amount of PD, it can

be discriminated between PD in liquid and in gaseous nitrogen, but it is necessary to detect a significant number of PDs. However, by evaluating the fall time of the PD waveform, the discrimination would be possible even with a small number of PDs. It is known that the deterioration characteristics of electrical insulation follows a bathtub curve [18]. If the number of PDs increases before dielectric breakdown, it is expected that most of the PDs will be discharged in gaseous rather than in liquid nitrogen. The authors believe that the discrimination of PDs based on the PD waveform itself becomes a powerful tool for condition monitoring of electrical insulation systems.

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