

Partial Discharge Current Pulse Waveform Analysis (PD-CPWA) Based on PD Mechanisms in Solid and Gas Media

N. Hayakawa^{1*}, Y. Sugimori¹ and H. Okubo²

¹Department of Electrical Engineering and Computer Science, Nagoya University,
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

²EcoTopia Science Institute, Nagoya University,
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

* E-mail : nhayakaw@nuee.nagoya-u.ac.jp

Abstract: This paper introduces a novel technique for partial discharge (PD) measurement and analysis: PD-CPWA (PD Current Pulse Waveform Analysis). PD-CPWA focuses on the PD current pulse waveform and its time transition from PD inception to breakdown (BD), which is closely related to PD mechanisms in electrical insulating materials. In this paper, the concept and principle of PD-CPWA are described, and the applications of PD-CPWA to PD characteristics of (1) epoxy spacer samples under thermal and electric combined stresses in GIS and (2) metallic particles contaminated in SF₆ gas on epoxy spacers in GIS are introduced.

INTRODUCTION

Partial discharge (PD) measurement has been recognized as an important diagnostic tool for electrical insulating materials in high-voltage power apparatus. However, physical mechanisms from PD inception to breakdown (BD) have not been well understood. Future PD measurement should be based on the physical mechanisms of PD inception, propagation, degradation and BD of the materials, which will contribute to the reliable insulation diagnosis of high-voltage power apparatus.

PD measurement for electrical insulating materials is quite difficult, because the PD signals are so faint and have the frequency component as high as the order of GHz. PD mechanisms are also quite complicated, since they depend on different physical and chemical parameters. However, the PD phenomena and mechanisms must be reflected in their current pulse waveforms. For example, the rise and fall times of a PD current pulse waveform are influenced by electron avalanche and/or streamer/leader discharge extension, and by diffusion and recombination of charge carriers, respectively [1].

We have been investigating PD characteristics and mechanisms of different insulating materials such as gases, liquids and solids. In this paper, we developed a useful PD measurement and analysis technique

referred to as "PD Current Pulse Waveform Analysis (PD-CPWA)". PD-CPWA can obtain not only individual PD current pulse waveforms with the time resolution of sub-nanosecond order, but also its time transition from PD inception to BD, with the PD detection sensitivity of 0.1 pC. The obtained PD current pulse waveforms can also be analyzed in terms of different parameters such as peak value, di/dt, rise-time, fall-time of a single pulse, time-interval of subsequent pulses and so on. This paper introduces the concept, principle and applications of PD-CPWA to PD characteristics in solid and gas media for GIS under a long-term ac voltage application.

CONCEPT AND PRINCIPLE OF PD-CPWA

When we measure PD generation characteristics and discuss their physical mechanisms of electrical insulating materials, PD current pulse waveform gives us a great deal of information. However, when we deal with the sequential PD generation characteristics and their physical mechanisms during long time duration from PD inception to BD, we often find the incompatible requirements on PD current pulse waveform measurement as follows:

- When precise PD current pulse waveforms have a priority to be measured, sequential PD generation characteristics are limited at most for several cycles under ac voltage application.
- When sequential PD generation characteristics have a priority to be measured, precise PD current pulse waveforms can not be obtained due to the unsatisfactory time resolution.

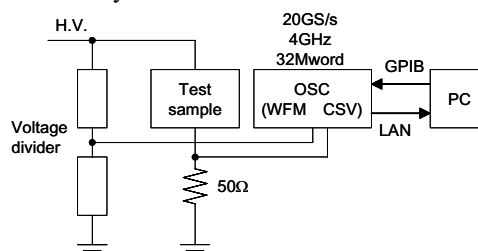


Fig. 1 Concept and principle of PD-CPWA

A digital oscilloscope with an infinite memory will overcome the above incompatibility on PD current pulse waveform measurement, which is, of course, not realistic. Then, we developed PD-CPWA. The concept and principle of PD-CPWA is schematically illustrated in Fig. 1. The PD current pulse signal is converted into the voltage signal through $50\ \Omega$ resistance as the detecting and matching impedance under the test sample, and fed into a digital oscilloscope (20 GS/s, 4 GHz, 32 MWord). Together with the noise reduction techniques, even a quite small PD signal with the charge magnitude as low as 0.1 pC and the rise time as short as sub-nanosecond order, such as in SF₆ gas, can be detected.

Once the oscilloscope is triggered, PD signal is measured within a preset time duration using the FastFrame function of the oscilloscope. Owing to the long memory of the oscilloscope, more than 6000 PD signals can be recorded with the time stamp. The applied ac voltage signal is also used as the reference signal in order to identify the generating time and phase angle of the corresponding PD signals. As the result, we can obtain the PD generation characteristics not steadily but only when PD signals are detected.

Each PD current pulse waveform obtained above is saved as WFM format in the oscilloscope and converted into CSV format through GPIB controlled by a personal computer. Then, a series of CSV files are transferred to the personal computer through LAN. If 2 sets of oscilloscopes and personal computers are available to be flexibly switched over, we can continue to obtain both PD current pulse waveforms and sequential PD generation characteristics without any time restriction from PD inception to BD.

Now, we can reproduce the sequential PD generation characteristics with each PD current pulse waveform in the personal computer. Then, the PD signals can be analyzed in terms of different parameters not only for a single PD current pulse waveform but also for its time transition. Examples of the analysis will be introduced in the next section.

APPLICATION OF PD-CPWA

(a) PD in epoxy spacer

PD-CPWA application to PD in an epoxy spacer for GIS is introduced. Figure 2 shows the experimental setup of an epoxy spacer model. High-voltage and grounded electrodes made of aluminum with the edge radius of 6 mm were embedded in the epoxy resin. The gap length between the both electrodes was 4 mm. The virgin sample of the epoxy spacer model was PD free up to 154 kV_{rms} under ac 60 Hz voltage application.

Simulating the operational condition of GIS, thermal stress was applied to the epoxy spacer models in an

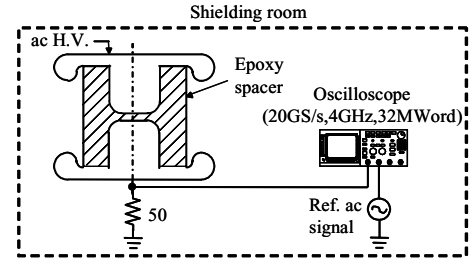


Fig.2 Experimental setup of epoxy spacer model

Table 1 Thermal stress condition for epoxy

Temperature [°C]	Heating duration [hour]	PDIV [kV _{rms}]	Time to BD t _{BD}	Number of PD pulses from PD inception to BD	
				Negative	Positive
105	40	125.2	2min 26s	60	1
140	40	122.4	12min 22s	12194	17336
150	15	150.7	33s	697	737
160	1	153.6	1min 55s	191	143
		150.4	1.7s	90	38
		147.4	4.7s	248	114
	5	114.4	> 3hours	-	-
180	1	136.4	10s	437	382
	5	141.0	11min 22s	3340	2026

oven for different temperatures and durations. Table 1 summarizes the thermal stress conditions for total 9 samples. Each sample was placed in SF₆ gas at 0.4 MPa. Then, electric stress was applied to the sample and generated PD. After the PD inception, the applied voltage was kept at the PD inception voltage (PDIV). The sequential PD generation characteristics were obtained by PD-CPWA from PD inception to BD.

The obtained PD generation characteristics and the analyzed PD parameters are shown in Fig. 3 for the sample with thermal stress of 180 °C for 5 hours. PDIV of the sample was 141.0 kV_{rms} and BD was induced at 11 minutes 22 seconds after the PD inception, where Fig. 3 corresponds to the last 60 seconds before BD. Total 5366 PD pulses (positive: 3340, negative: 2026) were generated from PD inception to BD. Such statistical data of PD generation characteristics for each sample are shown in Table 1.

Figure 3 shows (a) PD current pulse waveforms, time transitions of (b) PD current pulse height, (c) di/dt, (d) rise time, (e) fall time, (f) PD charge, (g) PD energy of each PD current pulse waveform, respectively, and (h) accumulated PD energy, (i) time interval of sequential PD pulses. PD charge was calculated by the integration of PD current pulse waveform, and PD energy was evaluated by the product of PD charge and applied voltage. The followings can be derived from Fig. 3:

- (1) PD current pulse waveform becomes larger and steeper with the elapse of time.
- (2) PD generation was not continuous, but intermittent from PD inception to BD.

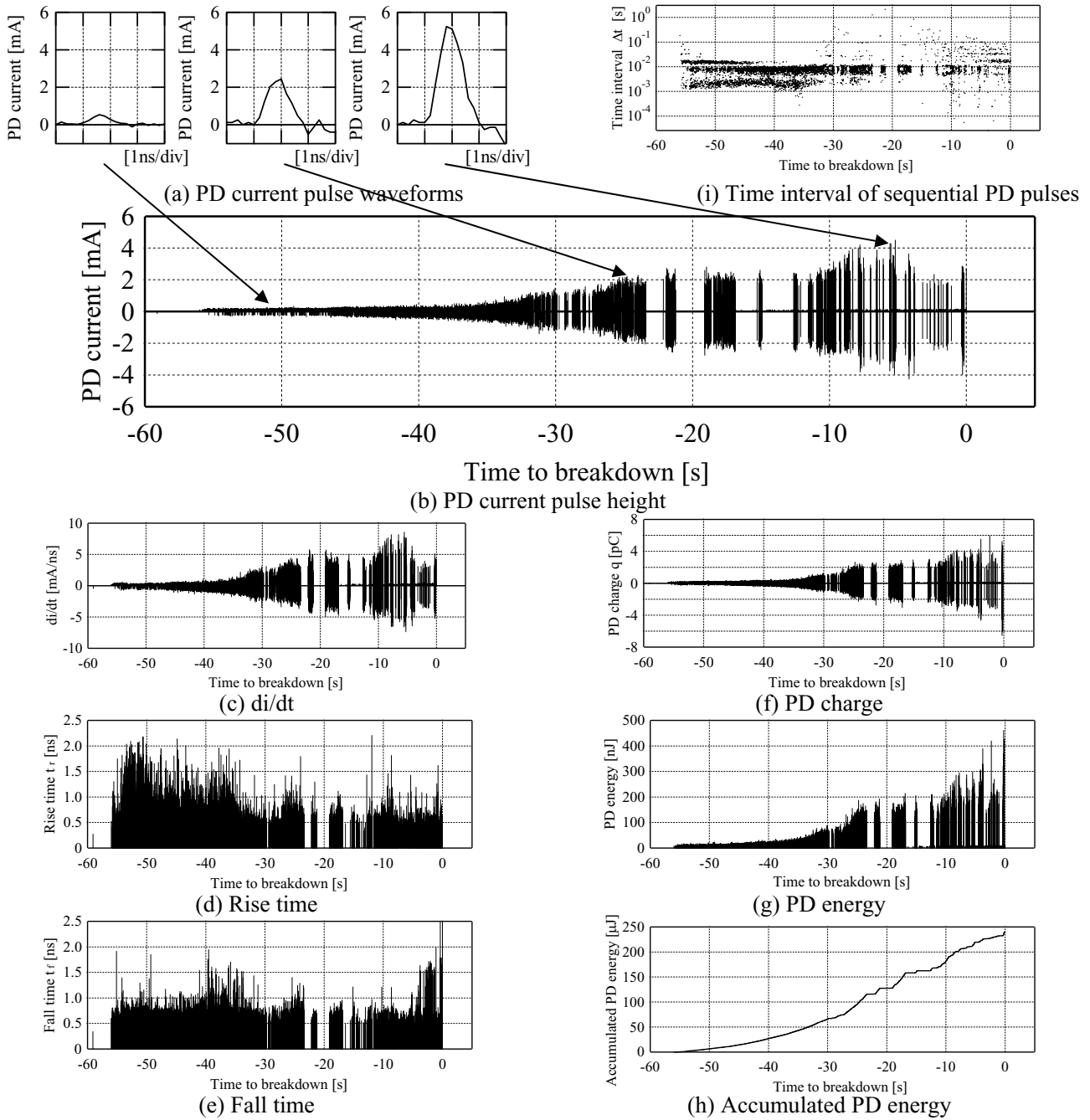


Fig.3 PD-CPWA for epoxy spacer model (180 °C, 5 hours)

- (3) Time transitions of di/dt , PD charge and PD energy were consistent with that of PD current pulse height.
- (4) Time transitions of rise time and fall time were not consistent with that of PD current pulse height.
- (5) Time interval of sequential PD pulses decreased into the order of microseconds before BD.

The above tendencies in PD generation characteristics were similar in most samples, irrespective of the difference in thermal stress conditions. Especially, when the elapsed time after the PD inception was normalized by the time to BD in each sample, the time transitions of PD generation characteristics could be

regarded to be similar [2]. Thus, some specific PD parameters to be closely related to the insulation degradation of epoxy spacer samples may be identified using PD-CPWA, which will contribute to elucidate the physical mechanisms of insulation degradation leading to BD of GIS.

(b) Creepage PD in SF₆ Gas

PD-CPWA application to the creepage PD in SF₆ gas is introduced. Figure 4 shows the experimental setup of a needle fixed on an epoxy plate between parallel plane electrodes in SF₆ gas at 0.1 MPa (dimensions are shown in Fig. 4). In order to measure PD current pulse waveform generating at the needle tip under ac 60 Hz

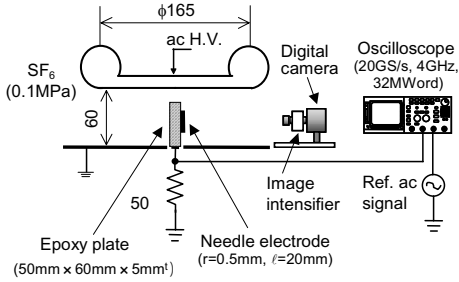


Fig.4 Experimental setup of needle on epoxy plate

Table 2 Arrangement of needle and epoxy

Electrode arrangement				
PDIV [kV _{rms}]	19.0	22.5	12.5	12.2
Applied voltage [kV _{rms}]	30.0	35.0	20.0	20.0

voltage application, a detecting and matching circuit with 50 Ω resistance was set under the epoxy plate. The detected PD signals were fed into the digital oscilloscope and analyzed by PD-CPWA.

Table 2 shows different arrangements of needle and epoxy plate with the measured PDIV. When PD-CPWA was applied to each arrangement, the applied voltage was set at about 160 % of PDIV, because the number of PD signals to be shown later decreased with the elapse of time. PD measurement under PD-CPWA was repeated in every 2 minutes for 30 minutes.

Figure 5 shows the time transition of averaged values and standard deviations of positive and negative PD current pulse heights in every 2 minutes, when the needle was fixed on the middle of epoxy plate. The PD current pulse height decreased drastically within the first 2 minutes and then gradually decreased or almost constant after 2 minutes. Figure 6 shows the time transition of di/dt in the negative PD current pulse waveform for different arrangements in Table 2. Note that the data are normalized by those just after the voltage application. The time transition of di/dt depended on the location of the needle fixed on the epoxy plate. The time constants of the decrease in di/dt were about 1, 2 and 5 minutes, respectively. The difference in the time constant will be interpreted by the charging characteristics and mechanisms on the epoxy plate as well as the resultant distortion of electric field distribution for each arrangement [3]. The

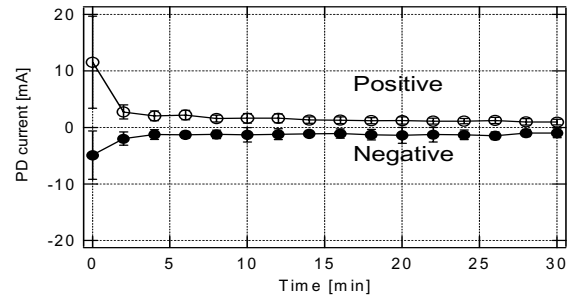


Fig.5 Time transition of PD current pulse height

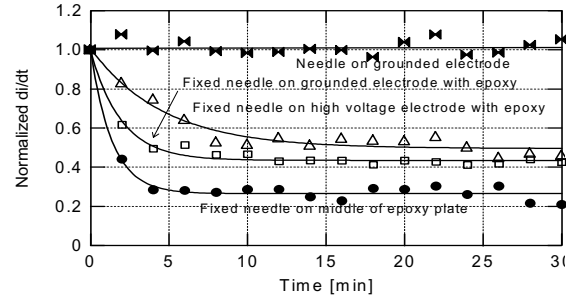


Fig.6 Time transition of di/dt

above measurement and discussion on the transition of PD parameters using PD-CPWA may contribute to locate the fixed particles on epoxy spacer and distinguish them from free particles in GIS.

CONCLUSIONS

In order to establish the reliable insulation diagnosis of high-voltage power apparatus, PD measuring technique with understanding discharge mechanisms should be developed. We developed “PD Current Pulse Waveform Analysis”, abbreviated to “PD-CPWA”, focusing on PD current pulse waveform including different physical processes on discharge inception, propagation and breakdown. The concept, principle and applications of PD-CPWA were introduced in this paper. PD-CPWA is expected to have a wide variety of application to different electrical insulating materials such as gas, liquid, solid, vacuum and their composite insulation systems.

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