Novel Measurement and Analysis System for Investigation of Partial Discharge Mechanism in SF_6 Gas

H. Kojima, N. Hayakawa, F. Endo, H. Okubo
Nagoya University
Furo-cho, Chikusa-ku
Nagoya 464-8603, Japan

Abstract-**An understanding of mechanism of partial discharge (PD) in SF_6 gas is critical for diagnosis of PD in electric power equipment and contributes to the optimization of the design of electric power applications. However, for complexity of PD characteristics under non-uniform electric field, the mechanism of PD in SF_6 is not comprehended enough. For this reason, we aim to reveal the PD mechanism by measuring current waveform, propagation characteristics and light emission of PD in SF_6 gas and analyzing these data. For this purpose, we have developed excellent measurement and analysis techniques.**

For an analysis of PD under ac voltage application, not only PD waveforms but also PD propagation property is essential. We have constructed partial discharge current pulse waveform analysis (PD-CPWA) system. This system has enabled us to observe PD current sequentially at high speed and analyze the propagation of PD current pulse statistically. By the application of PD-CPWA system to diagnosis of PD activity due to the metallic particle in SF_6, we could identify the particle type and size.

On the other hand, for an analysis of PD under impulse voltage application, an ultra high-speed PD measurement by various methods is extremely important. In order to investigate the impulse PD mechanism spatially and temporally, the simultaneous measurement of current and light emission intensity waveforms, streak and still light emission images and temporal evolution of spectrum of PD light emission have been carried out. By using this synchronous ultra-high speed PD measurement system, we revealed the change of light emission from decomposition products depending on the step propagation of leader discharge.

I. INTRODUCTION

SF_6 gas is widely used for insulation in gas insulated power equipment because of its good characteristics. An understanding of mechanism of partial discharge (PD) in SF_6 gas is significant for diagnosis of PD in electric power equipment. Moreover, an analysis of PD mechanism contributes to the optimization of design of electric power applications.

Gas insulated switchgears (GISs) is typical one of gas insulated power equipments. Their high reliability, low maintenance and compact size have made them the primary choice for many utilities. Nevertheless, insulation defects inside GIS can be a serious threat to safe operation of GIS and can lead to costly disruption of supply. Thus, the earlier insulation defect can be detected, the lower breakdown risk will be achieved. As insulation failure usually starts with partial discharge (PD) activity, several studies have been performed to use PD measurements as a diagnostic method for detecting defects and preventing major insulation breakdown [1]. In addition, the PD in SF_6 gas is represented by repeat transition from streamer to leader discharge [2], and by witch resulting in breakdown at last is known. However, the PD under non-uniform electric field is complicated, so the PD phenomenon, such as PD generation and progress characteristics is not clear.

From above viewpoints, we have been investigating PD mechanisms in SF_6 gas. In this paper, we talk about developed useful PD measurement and analysis techniques for ac and impulse voltage application, respectively. Then, as fruitful results by these novel measurement and analysis system, we represent about a detection of particle size in gas gap for ac voltage application and discuss characteristics of leader discharge progress for impulse voltage application.

II. PD ANALYSIS FOR AC VOLTAGE APPLICATION

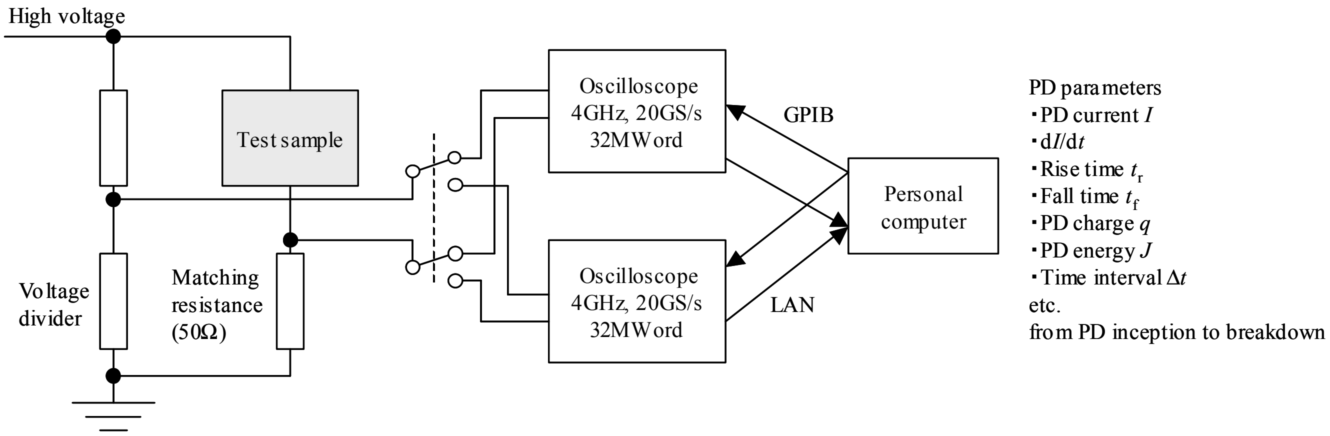
For an analysis of PD under ac voltage application, not only PD waveforms but also PD propagation property is essential. We have constructed partial discharge current pulse waveform analysis (PD-CPWA) system. This system has enabled us to observe PD current sequentially at high speed and analyze the propagation of PD current pulse statistically.

A. PD-CPWA system

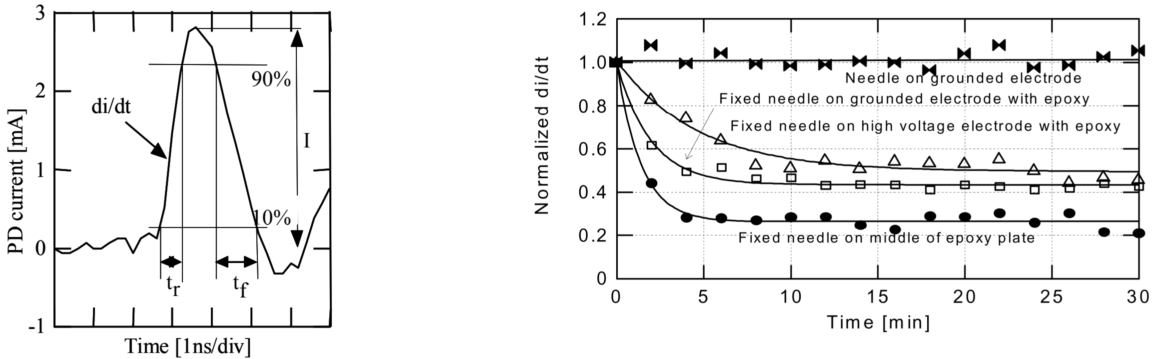
Constructed PD-CPWA system is illustrated in Fig. 1. The PD current pulse signal is converted into the voltage signal through 50 Ω resistor as the detecting and matching impedance under the test sample, and fed into a digital oscilloscope (4 GHz, 20 GS/s, 32 MWord). With the noise reduction techniques, this system has the sensitivity of 0.1 pC.

PD signal is measured within preset time duration of the oscilloscope. The applied ac voltage signal is also used as the reference signal in order to identify the generating time of the corresponding PD signals. Therefore, only PD signals are recorded, and data between PD signals are not recorded. As the result, we can obtain the PD signals with highly compressed and memory saving data, and more than 6,000 signals of PD current pulse waveforms can be recorded with the time resolution of the order of sub-nanoseconds.

978-1-4244-1933-3/08/$25.00 ©2008 IEEE



(a) Schematic illustration of PD-CPWA system.



(b) Definition of PD parameters.

(c) Example of PD-CPWA data acquisition result. Time transition of steepness dI/dt for creepage PD [3].

Fig. 1. Partial discharge current pulse waveform analysis (PD-CPWA).

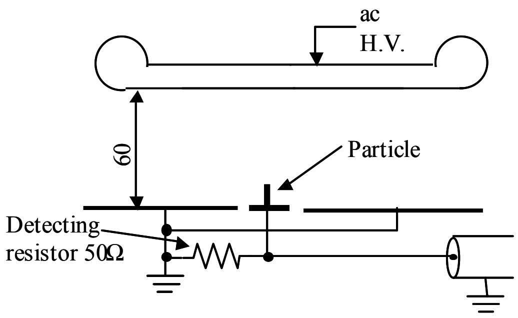
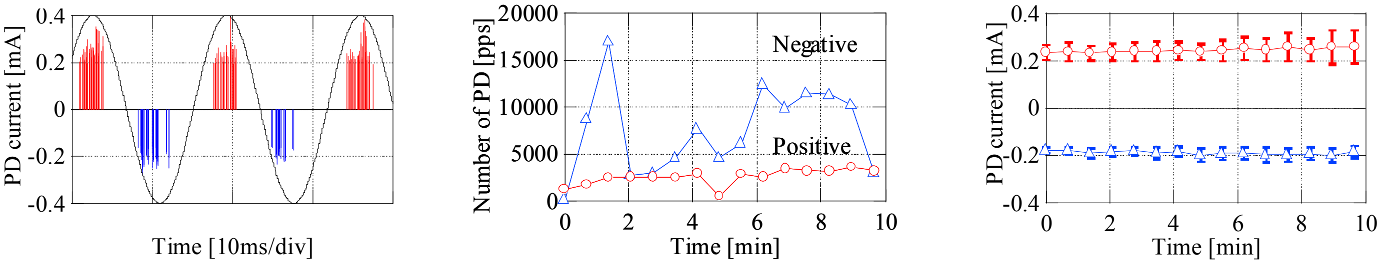


Fig. 2. Electrode and particle setup.

Using 2 sets of oscilloscopes and personal computers to be flexibly switched over by a high-frequency switch, we can continue to obtain both PD current pulse waveforms and sequential PD generation characteristics without any time restriction [3, 4].

By constructed PD-CPWA system, we can analyze the PD signals by means of different parameters not only for a single PD current pulse waveform but also for its temporal revolution. Such statistical analysis will be useful for us to understand the PD characteristics and to investigate the PD mechanisms.

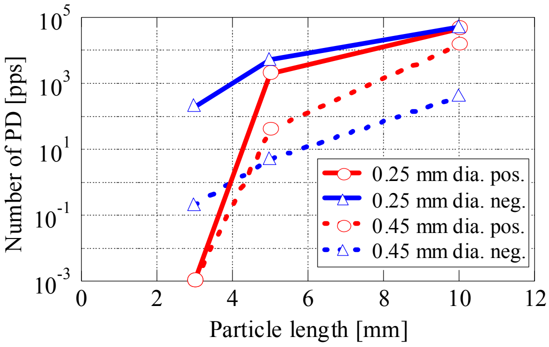


(a) Phase vs. PD characteristics.

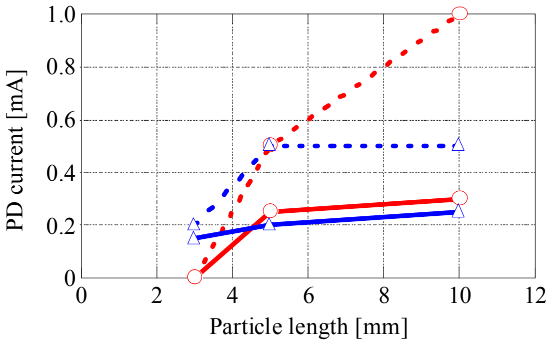
(b) Temporal variation of PD pulse number.

(c) Time dependence of PD current.

Fig. 3. PD propagation in the case of particle in a gap. (particle length: 5 mm, diameter: 0.25 mm)



(a) PD pulse number.



(b) PD current.

Fig. 4. Dependency of PD characteristics on particle length.
(particle in a gap)

B. Detection of particle size in gap

Figure 2 shows examined defect, which simulated a particle in a gas gap. The gap length of the parallel plane electrode was 60 mm. A particle was vertically attached on the grounded electrode. A material of the particle was aluminum. Applied field strength of 60 Hz ac was 2.0 kV_{rms}/mm, which is almost equal to the normal operational field strength of GIS. The polarity was expressed as the polarity of a particle tip. SF_6 gas pressure was 0.4 MPa. Every PD pulse of sub-ns was accurately recorded in PD-CPWA, and was analyzed from various physical viewpoints [5].

Figure 3 shows the typical experimental results. PD was measured for 10 minutes. PD inception voltage was 1.0 kV_{rms}/mm. PD characteristics are greatly influenced by particle length and diameter. As shown in Fig. 4, in the case of a 3 mm long particle, through negative PD appeared, positive PD did not appear. When particle becomes long, the PD pulse number increases in comparably. The PD pulse number was larger at thin particles than at big ones. Moreover, in the case of particles 0.25 mm in diameter, the PD pulse number and PD current were almost equal between positive and negative PD for particles longer than 5 mm. However, in the case of particle 0.45 mm in diameter, the PD pulse number and PD current were much greater at the positive PD than at the negative one. These results implies that particle size can be estimated correctly by considering these tendency of the PD pulse number and current.

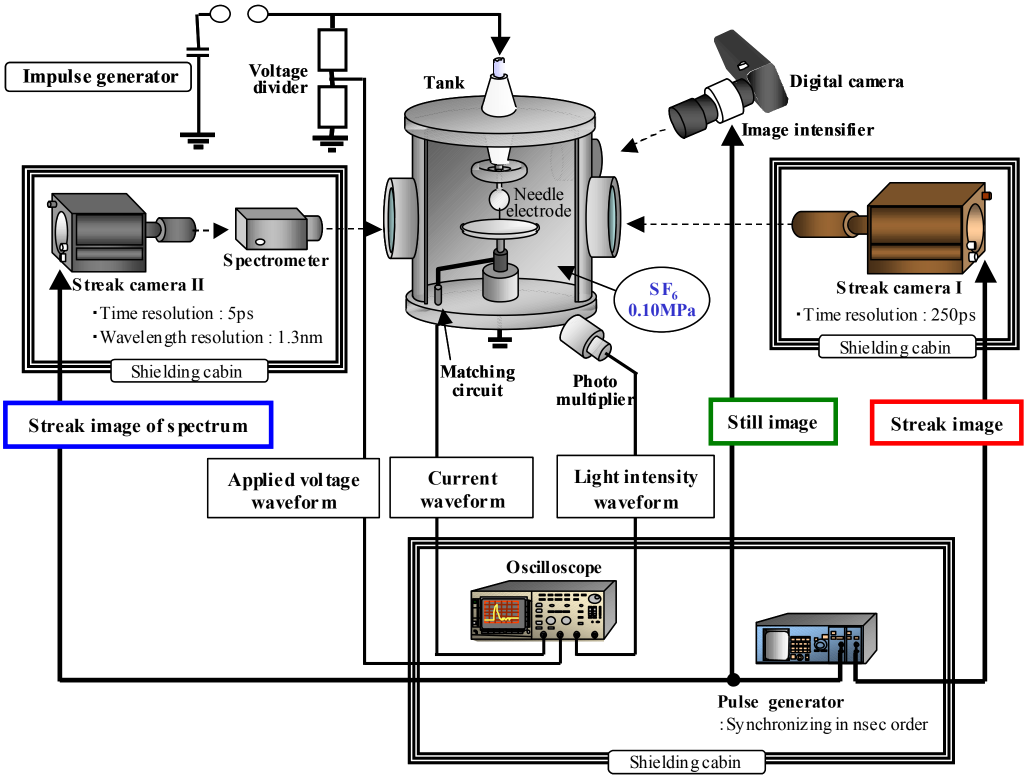
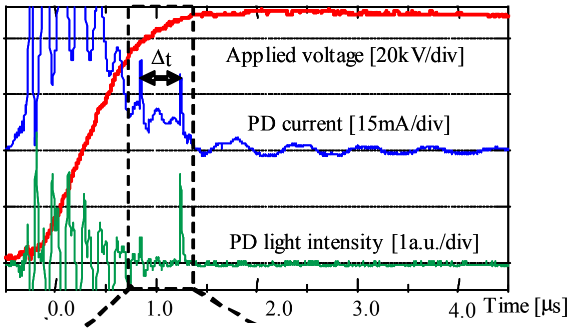
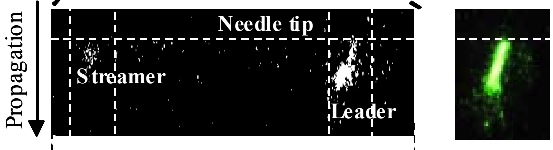


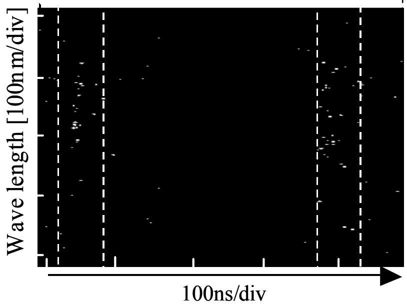
Fig. 5. Ultra high-speed synchronous PD observation system for impulse voltage application.



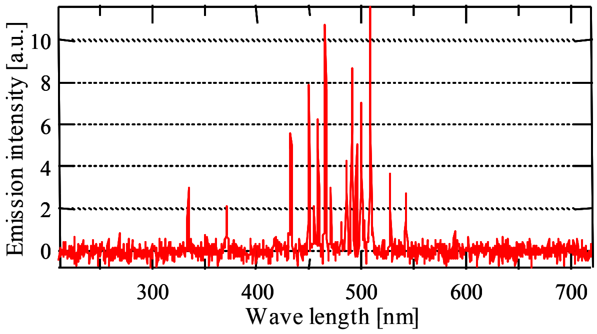
(a) PD signal waveforms



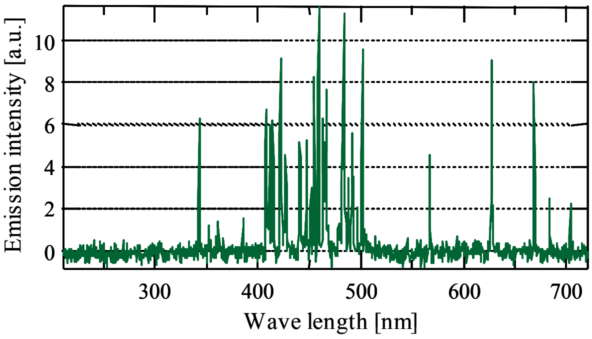
(b) Streak image of PD (c) Still image of PD



(d) Streak image of PD light emission spectrum



(e) Spectrum of streamer



(f) Spectrum of leader

Fig. 6. Electrical and optical PD signals by ultra high-speed synchronous PD observation system for impulse voltage application.

III. PD ANALYSIS FOR IMPULSE VOLTAGE APPLICATION

For an analysis of PD under impulse voltage application, an ultra high-speed PD measurement by electrical and optical methods is extremely important. In order to investigate the impulse PD mechanism spatially and temporally, we have constructed the ultra high-speed PD observation system, which allows the simultaneous measurement of current and light emission intensity waveforms, streak and still light emission images and temporal evolution of spectrum of PD light emission.

A. Ultra high-speed synchronous PD observation system

Figure 5 shows the experimental setup for the measurement of PD phenomenon under needle-plane electrode system in SF_6 gas under positive lightning impulse voltage application. The high voltage side electrode with the tip diameter of 1 mm was fixed on the sphere electrode, and the gas length between needle electrode and plane electrode was 40 or 70 mm. The experimental vessel was filled with SF_6 gas at the gas pressure of 0.1 MPa.

A digital oscilloscope (2 GS/s, 1 GHz) through a matching circuit observed the applied impulse voltage and PD current pulse waveforms. The still image and the intensity of PD light emission were observed by using a digital camera with an image intensifier and a photomultiplier tube, respectively. The streak image of PD light emission was recorded by an ultra high speed streak camera (streak camera I, time resolution < 250 ps) to observe the propagation process of the impulse PD. Moreover, the spectrum of the PD light emission was recorded by an ultra high speed streak camera (streak camera II, time resolution < 5 ps) with spectrometer to observe the variation of PD light emission spectrum. The gate signal from pulse generator enabled us to measure these electrical and optical signals simultaneously and synchronously [6].

B. Progress of leader discharge

Figure 6 shows PD signal waveforms, streak and still image of PD and streak image of PD light emission spectrum in the case of applied voltage of 85 kV. PD signal consists of plural pulse signals (PD_{1st}, PD_{2nd}), and a streamer-leader transition occurs. By the constructed ultra high-speed synchronous PD observation system, we can separate such as plural pulse signals. In streamer discharge (PD_{1st}), the light emission between 350 nm and 560 nm was mainly observed. On the other hand, in leader discharge (PD_{2nd}), the light emission above 560 nm was also observed. The light emission above 560 nm in leader discharges contains the emission due to the deexcitation of fluorine atom, e.g. 623.9 nm, 634.8 nm, 685.6 nm, 690.2 nm and 703.7 nm [7]. Fluorine atoms will be generated by the dissociation of SF_6 molecules [8].

Figure 7 shows an intensity ratio (I_{long}/I_{total}) of the light emission above 560 nm to the total light emission as a function of PD step number in the case of gap length of 70 mm. I_{long}/I_{total} increases according to the progress of PD step. However, before the end of propagation of PD step, I_{long}/I_{total} tends to be saturated or to decrease. This tendency will imply

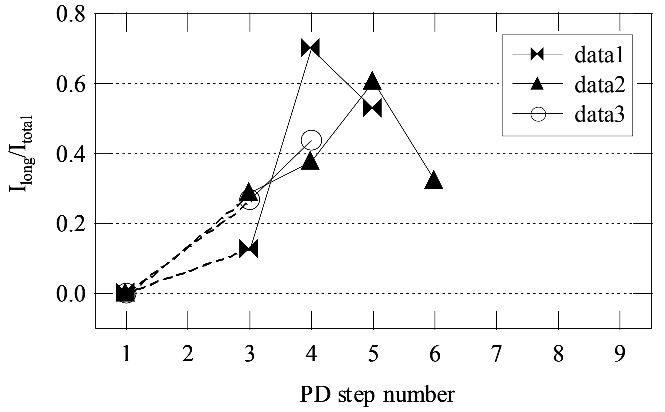


Fig. 7. Intensity ratio of light emission above 560 nm to total light emission as a function of PD step number.

a decrement of PD energy before the end of PD step propagation.

IV. SUMMARY

We have developed the PD-CPWA system and ultra high-speed synchronous PD observation system. The former system enables us to observe PD signals sequentially and to analyze the propagation of PD signals statistically. These features are very practical for the investigation of PD mechanisms under ac voltage application. The latter system is extremely useful for the measurement of PD under impulse voltage application, because the progress of PD is very fast phenomenon of the order of nanoseconds. By using PD-CPWA system, we revealed that the analysis of PD pulse number and PD current permitted us to distinguish particle size in gas gap. Then, by using ultra high-speed synchronous PD observation system, we demonstrated the relation between the PD progress and PD light emission spectrum.

REFERENCES

[1] I.A. Metwally, "Status review on partial discharge measurement techniques in gas-insulated switchgear/lines", *Electric Power Systems Research*, vol. 69, pp. 25-36, 2004.

[2] I. Gallimberti and N. Wiegart, "Breakdown mechanisms in electronegative gases", *Proc. 5th Intl. Symposium on Gaseous Dielectrics*, pp. 61-79, 1987.

[3] H. Okubo and N. Hayakawa, "A novel technique for partial discharge and breakdown investigation based on current pulse waveform analysis", *IEEE Trans. DEI*, vol. 12, pp. 736-744, 2005.

[4] N. Hayakawa, Y. Sugimori, and H. Okubo, "Partial discharge current pulse waveform analysis (PD-CPWA) based on PD mechanisms in solid and gas media", *Proc. 2005 Intl. Symposium on Electrical Insulating Materials*, vol. 3, pp. 812-815, 2005.

[5] F. Endo, T. Okusu, K. Nishizawa, N. Hayakawa, M. Yoshida, T. Ogawa, and H. Okubo, "High speed measurement and analysis of partial discharge pulses in SF_6 gas insulation system", *Proc. 15th Intl. Symposium on High Voltage Engineering*, T7-152, 2007.

[6] H. Kojima, Y. Ohta, S. Yoshida, N. Hayakawa, F. Endo, and H. Okubo, "Partial discharge mechanism by spectrum measurement under impulse voltage condition in SF_6 and gas mixtures", *Proc. 15th Intl. Symposium on High Voltage Engineering*, T7-182, 2007.

[7] H. Dingle, "The spectrum of fluorine (F I)", *Proc. the Royal Soc. of London, Series A, Containing Papers of a Mathematical and Physical Character*, vol. 113, No. 764, pp. 323-334, 1926.

[8] I. Sauers and G. Harman, "A mass spectrometric study of positive and negative ion formation in an SF_6 corona. Part I: sources of sulphur-fluorine ions", *J. Phys. D*, vol. 25, pp. 761-773, 1992.