CORRELATION BETWEEN UHF ELECTROMAGNETIC WAVEFORMS AND PARTIAL DISCHARGE CURRENT WAVEFORMS IN GIS

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Abstract: Ultra-high frequency (UHF) method is popular for the on-site monitoring of partial discharge (PD) in GIS, by detecting the electromagnetic wave with a frequency range of several hundred MHz to several GHz. In order to improve the availability of the UHF method, it is required to clarify the correlation between PD current pulse waveforms and electromagnetic waveforms. PD current pulse waveforms and electromagnetic waveforms emitted from PD were synchronously measured. As a result, we obtained the frequency spectrum characteristics of the electromagnetic waves depending on the rise and fall time of the PD current pulse waveforms. Then, by considering the propagation characteristics, we could find the good correlation in spectrum between the PD current pulse waveforms and the electromagnetic waveforms. This result indicates the physical background of UHF PD detection technique.

1 INTRODUCTION

The ultra-high frequency (UHF) method is becoming popular for the on-site monitoring of GIS, because of its features such as high sensitivity and high S/N ratio on site. Therefore, the studies on the UHF method (the measurement method of PD-induced electromagnetic-wave (EM-wave), the propagation of EM-wave in GIS, etc.) are actively studied [1-4]. On the other hand, measuring and analyzing PD current pulses are effective to understand PD physics and identify the defect. Therefore, for further development of the UHF method it is important to clarify the relation between the emitted EM-waves and PD current pulses. The authors have systematically studied the particle-initiated PD characteristics in order to enable to identify the defect in GIS [5-7].

In this paper, the relation between EM-waveforms and PD current pulse waveforms from the particle-initiated PD are analyzed. Moreover, we discuss the estimation method of PD current pulse waveforms from EM-waveforms.

2 EXPERIMENTAL METHOD

Figures 1 and 2 show electrode and experimental setup. A metallic particle (ϕ0.25 mm, ℓ= 3, 5, 10 mm) was fixed vertically on a grounded electrode of a parallel-plane electrode system (gap length: 60 mm). As GIS is usually operated under the electric field strength of 2-2.5 kV_{rms}/mm on high voltage conductor, the applied voltage was selected as 120 kV_{rms} (2 kV_{rms}/mm). SF_6 gas pressure was 0.4 MPa. PD was measured with PD-CPWA system, which can analyze every PD current pulse on various physical quantities [8]. Moreover, using the semicircular dipole antenna (diameter: 70,100 mm, slit width: 1 mm) as a UHF sensor, EM-waveforms and PD current pulse waveforms emitted from the particle were synchronously measured. The frequency spectra of these waveforms were analyzed. The polarity of PD is expressed by that of the high voltage electrode.

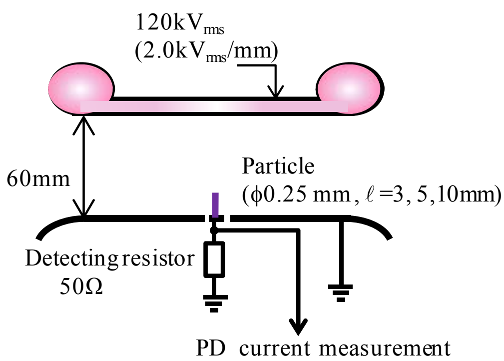


Figure 1 Electrode setup.

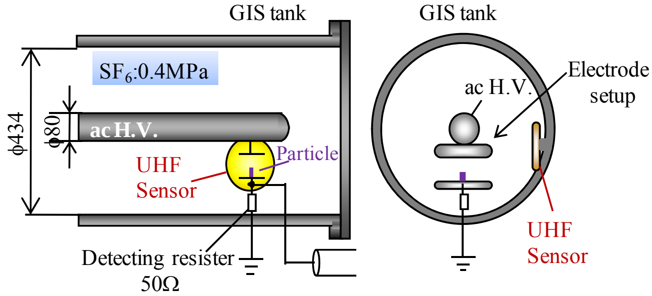


Figure 2 Experimental setup.

3 EXPRIMENTAL RESULTS AND DISCUSSION

In section 3.1, the correlation between the charge of PD pulse and EM-wave intensity was measured and the dispersion of the correlation was analysed. For the main cause of dispersion, the change of EM-wave spectrum based on PD current waveform was discussed in section 3.2. Finally, by using the measurement results of the EM-wave propagation characteristics, we discuss the estimation method of EM-wave from PD current, in section 3.3.

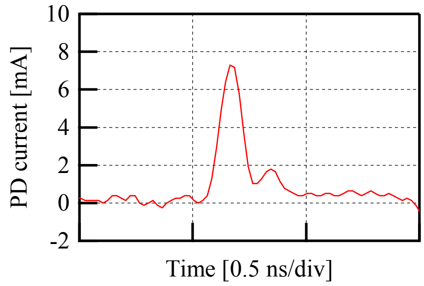
3.1 Correlation between the charge of PD pulse and EM-wave intensity

Figure 3 shows the PD current waveform and definition of EM-wave intensity. The intensity of EM-wave was defined as the difference between the peak value of the waveform and the mean value before PD generation. Figure 4 shows correlation between the charge of PD pulse and EM-wave intensity. In Fig. 4, the EM-wave intensity was proportional to the charge of PD pulse. The mean square dispersion of the correlation is 0.93, when the correlation was approximated by proportional line. This EM-wave measurement includes the radio frequency noise, but the noise level was enough low.

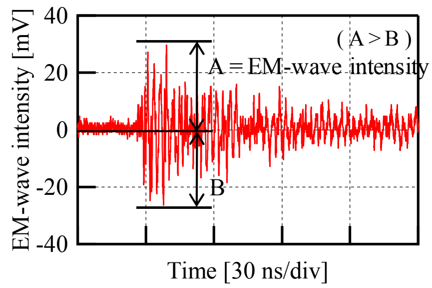
It is assumed that the charge of PD correlates to EM-wave intensity. Therefore, the correlation is compared and analyzed [6, 7]. However, even if the charge of PD pulse is constant, actual PD characteristics of the PD current pulse vary. Moreover, it is considered that if the particle size varies, there is a possibility that the EM-wave emission characteristics of PD vary. Therefore it is important to understand the feature of UHF method. We consider the followings are main causes of the dispersion in Fig.4 ; 1. Variation of PD current pulse, and 2. Superposition of successive PD pulse

3.1.1 Variation of PD current pulse Figure 5 shows the distribution of the rise time and PD current. Various rise time and current of PD current pulse waveforms are generated under the same experimental condition. Even if the PD current was constant, the rise time may disperse. PD characteristics in AC voltage vary depending on the voltage phase or the space charge [9]. In this way, various types of PD current pulse occur in the AC voltage. These PD current pulses emit various types of EM-waves. Such differences of the EM-waves characteristics could make the dispersion of the acquired EM-waves, shown in Fig.4.

3.1.2 Superposition of successive EM-wave EM-wave from PD could emit successively in less than 50-100 ns. In this situation, there is a possibility that EM-wave intensity was acquired with an error value. Figure 6 shows (a) the definition of the attenuation time constant and (b) measured result of time constant of EM-waveforms on each PD current. We approximate the envelope of the EM-waveforms by the exponential function. In our experimental setup, time constant was around 40-50 ns in any PD current intensity. It takes 200 ns



(a) PD current waveform



(b) Definition of EM-wave intensity

Figure 3 PD current waveform and definition of EM-wave intensity.

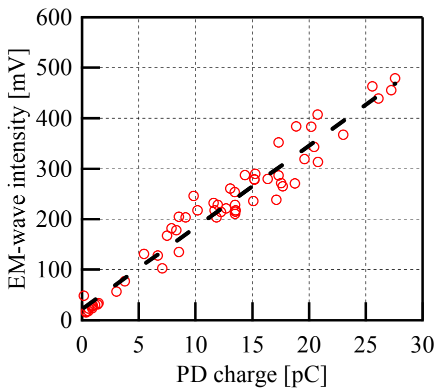


Figure 4 Correlation between charge of PD pulse and EM-wave intensity (ϕ 0.25 mm, ℓ =10 mm).

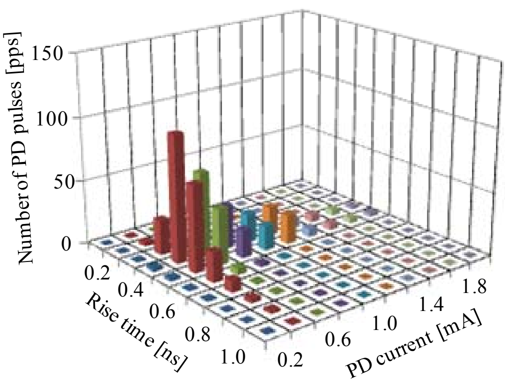
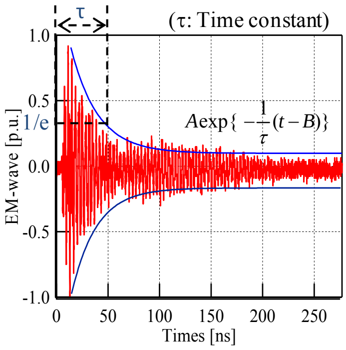
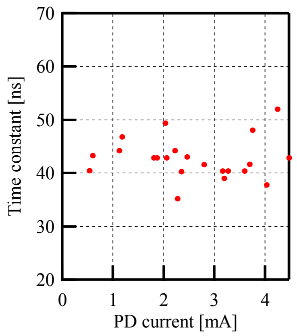


Figure 5 Distribution of the rise time and current of PD current pulses (ϕ 0.25 mm, ℓ =3 mm).



(a) Definition of attenuation time constant.



(b) Measured time constant of EM-wave

Figure 6 Time constant of EM-waves of each PD current (ϕ 0.25 mm, ℓ =5 mm).

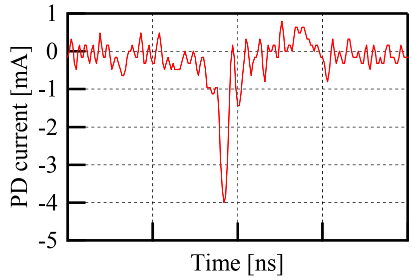
before the EM-wave intensity decay to the noise level. Therefore, if the successive PD pulses are generated in 50 ns, the second PD cannot be detected. Moreover, if the successive PD pulses are generated within 50-200 ns, the EM-wave intensity is detected to be larger than the actual EM-wave intensity.

3.2 EM-wave spectrum based on PD current waveform

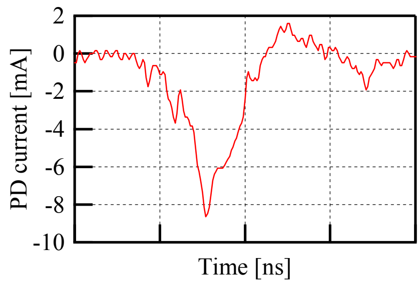
To study the EM-wave spectrum based to PD current waveform, two types of single pulse PD current waveforms shown in Fig. 7 were compared and analyzed: (a) PD current waveform with short rise time and fall time, and (b) PD current waveform with long rise time and fall time. Figure 8 shows the spectra of the PD current waveform and EM-waveform emitted from PD current shown in Fig. 7. In case of Fig. 7(a), the spectrum of the PD current shows not only low-frequency, but also high-frequency content. On the other hand, in case of Fig. 7(b), the spectrum of PD current shows only low-frequency content. Moreover, the spectra of the EM-waves denote the same tendency of the PD current spectrum, in which EM-wave spectrum corresponds well to PD current waveform. From this result, using the correlation in spectrum between PD current and EM-wave, the correspondence between PD current waveform and EM-waveform can be discussed, which suggests the possibility to estimate the PD current waveform from the EM-wave.

3.3 Relationship between PD current and EM-wave on frequency spectra

In Fig. 8, PD current spectrum mostly consists of the low-frequency content. Moreover, the spectrum of PD current and EM-wave shows good correlation on low-frequency content. Therefore, using the sensor diameter 100 mm of UHF sensor, we focused on the relationship between PD current and EM-wave in low-frequency spectrum less than 1300 MHz.

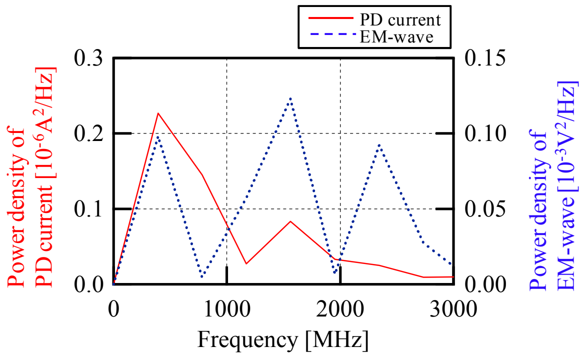


(a) Short rise time and fall time

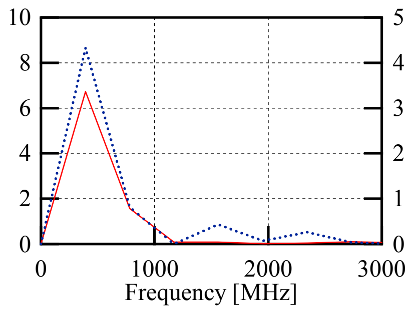


(b) Long rise time and fall time

Figure 7 Two types of PD current waveforms (ϕ0.25 mm, ℓ =10 mm).



(a) Short rise time and fall time



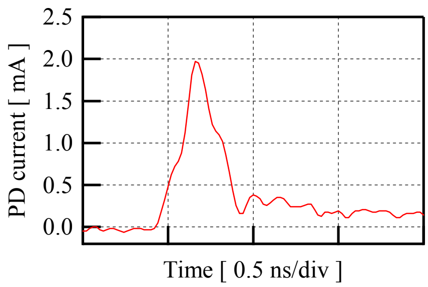
(b) Long rise time and fall time

Figure 8 Comparison of PD current spectrum and EM-wave spectrum (ϕ0.25 mm, ℓ =10 mm, sensor diameter 70 mm).

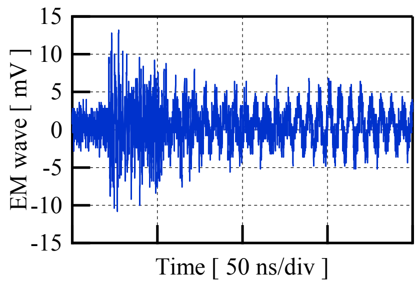
Figure 9 shows the PD current waveform and EM-waveform emitted from the same PD. Figure 10 shows the frequency spectra of the PD current waveform and EM-waveform shown in Fig. 9. In the spectrum analysis, we analyse for 20 ns in the PD current waveform, and for 200 ns in the EM-waveform. The spectrum of PD current waveform extends to high frequency, however, the intensity becomes weaker at the higher frequency. On the other hand, the spectrum of the EM-wave has large peaks in 90 MHz, 450 MHz, and 870 MHz.

The EM-wave radiation characteristics from the PD current, the propagation characteristics of EM-wave and the frequency characteristics of UHF sensor cause the differences between PD current spectrum and EM-wave spectrum.

To study the relationship between the spectra of PD current waveform and EM-waveform, we measured the propagation characteristics from particle to UHF sensor (including frequency response characteristics of UHF sensor) shown in Fig. 11. In Fig. 11, we applied the sinusoidal signal that has the constant intensity in 0-3 GHz to the particle, and measured the responses on UHF sensor by the spectrum analyzer. Using the propagation characteristics, the EM-wave spectrum in the UHF sensor was estimated from PD current spectrum. Figure 12 shows the comparison of estimated spectrum and measured EM-wave spectrum shown in Fig. 10(b). Both of the spectra are normalized by the peaks of 450 MHz. The estimated spectrum means the multiplication of the PD current spectrum in Fig. 10(a) and the propagation spectrum in Fig. 11. In Fig. 12, the peaks of the estimated spectrum agree well with those of the measured spectrum less than 800 MHz. Therefore, by clarifying the propagation characteristics the relationship between PD current spectrum and EM-wave spectrum can be expressed. On the other hand, in 800-1300 MHz, the intensity of the measured spectrum is weaker than that of the estimated spectrum. We consider it is due to the following sequential frequency characteristics of EM-wave.



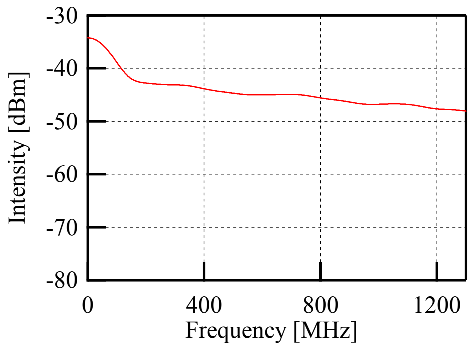
(a) PD current waveform



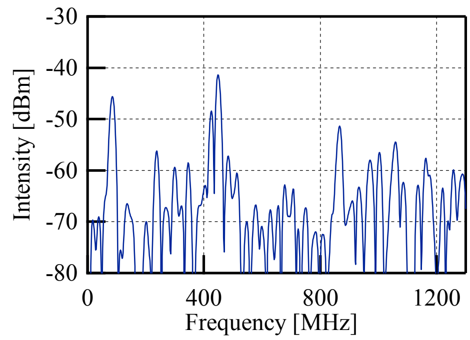
(b) EM-waveform

Figure 9 PD current and EM-waveforms (ϕ0.25 mm, ℓ =5 mm).

Figure 13 shows the sequential frequency characteristics of EM-waveform. In this figure, the EM-waveform is analyzed by 2.56 ns (128 point) with each 2 ns step. In 400 MHz, EM-wave intensity remains in more than 100 ns. On the other hand, in the 800-1600 MHz, EM-wave intensity only remains in less than 50 ns. Therefore, when the whole EM-waveform is analyzed like Fig. 10(b), the EM-wave intensity less than 800 MHz content becomes greater than that in 800-1300 MHz on our experimental setup. We consider that measuring the more detailed propagation characteristics is required to improve the agreement shown in Fig 12.



(a) PD current waveform



(b) EM-waveform

Figure 10 Frequency spectra of PD current and EM-waveforms (ϕ0.25 mm, ℓ =5 mm).

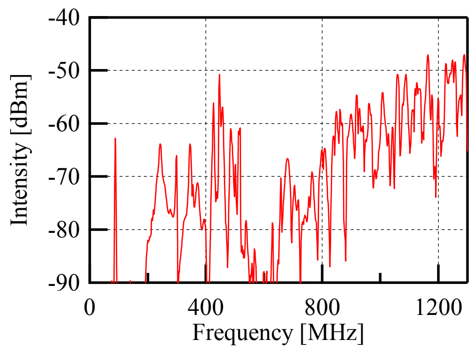


Figure 11 Propagation characteristics from particle to UHF sensor (ϕ0.25 mm, ℓ =5 mm).

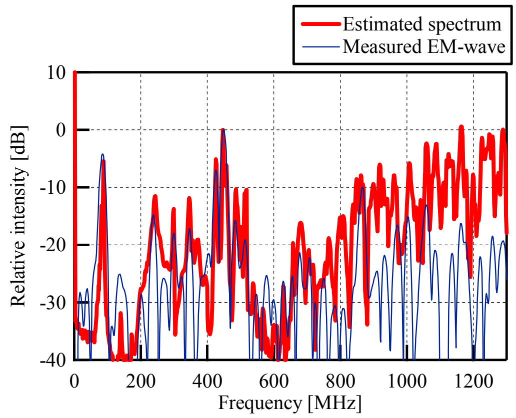


Figure 12 Comparison of estimated and measured EM-wave spectrum (ϕ0.25 mm, ℓ =5 mm).

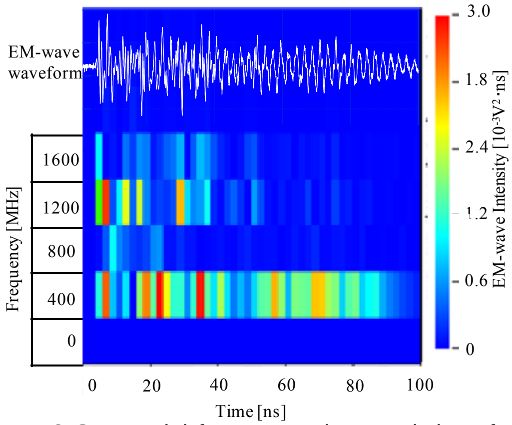


Figure 13 Sequential frequency characteristics of EM-waveform (ϕ0.25 mm, ℓ =5 mm).

4 CONCLUSIONS

PD current pulse waveforms and EM-waveforms emitted from PD were synchronously measured and analyzed. Following results were obtained.

(1) The relationship between PD current and EM-wave intensity was measured and analyzed. In particular, it is acquired that EM-wave spectrum varies depend on the rise time and fall time of PD current waveform. From these results, it is clarified that the EM-wave intensity is proportional to the charge of PD pulse with some dispersion of the variety of the PD current characteristics.

(2) We measured the propagation characteristics from the defect particle to UHF sensor. By using the propagation characteristics, the correlation between PD current spectrum and EM-wave spectrum was expressed. As a result, we discuss the estimation method of EM-wave from PD current. We consider that these results suggest the possibility to estimate the PD current waveform from the EM-wave.

5 REFERENCES

[1] M. Hikita, S. Ohtsuka and T. Teshima, “Electromagnetic (EM) Wave Characteristics in GIS and Measuring the EM Wave Leakage at the Spacer Aperture for Partial Discharge Diagnosis”, IEEE Trans. on DEI, Vol.14, No.2, pp.453-460, 2007

[2] T. Hoshino, M. Hanai and N. Kobayashi, “Online Source Recognition of Partial Discharge for Gas Insulated Substations Using Independent Component Analysis”, IEEE Trans. on DEI, Vol.13, No.4, pp.892-902, 2006

[3] T. Yamagiwa and F. Endo, “Partial Discharge and its Application to Gas Insulated Switchgear”, Gaseous Dielectrics X, pp.123-128, 2004

[4] T. Kato, F. Endo and S. Hironaka, “Sensitivity Calibration of UHF Partial Discharge Monitoring System in GIS”, T.IEE Japan, Vol.122-B, No.11, pp.1226-1231, 2002

[5] H. Okubo, F. Endo, N. Hayakawa, H. Kojima and M. Yoshida, “UHF Technique and Current Pulse Waveform Analysis for Partial Discharge Measurement”, CIGRE SC D1-Colloquium, D1-221, 2009

[6] M. Yoshida, K. Suzuki, H. Kojima, N. Hayakawa, M. Hanai, F. Endo and H. Okubo, “Partial Discharge Signal Evaluation of UHF Technique in Accordance with Current Pulse Waveform Measurement”, CMD2010, C2-3, pp.485-488, 2010

[7] M. Asai, K. Nishizawa, N. Hayakawa, F. Endo, M. Yoshida, K. Uchida, H. Okubo, “Detail Analysis of Particle-initiated Partial Discharges in SF_6 Gas for Condition Monitoring of GIS”, ISH2009, D-11, 2009

[8] H. Okubo and N. Hayakawa, “A Novel Technique for Partial Discharge and Breakdown Investigation Based on Current Pulse Waveform Analysis”, IEEE trans. on DEI, Vol.12, pp.736-744, 2005

[9] T. Takahashi, T. Yamada, N. Hayakawa, H. Okubo, “Power Frequency Dependence of Space Charge Behavior and Partial Discharge Characteristics in SF_6 Gas”, IEEE Trans. on DEI, Vol.7, No.1, pp.152-160, 2000