MEASUREMENT OF PD CURRENT WAVEFORMS IN SF_6 GAS WITH A SUPER HIGH FREQUENCY WIDE BAND MEASUREMENT SYSTEM

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Abstract: This paper described sophisticated measurements of partial discharge (PD) current waveforms in SF_6 gas with a super high frequency (SHF) wide band measurement system (SHF_PDPW system). The SHF_PDPW system consists of a 32 GHz or a 20 GHz digital oscilloscope and a plane to a specially arranged needle electrode system used by a SMK type coaxial connector. They are directly connecting with a 40GHz coaxial cable through a 26.5 GHz attenuator. Using this system, we measured PD current pulses changing the following parameters; *i.e.*, the needle electrode length *l*, applied voltage *Va*, SF_6 gas pressure *P*, and frequency bandwidth *fBW* of the oscilloscope. We discussed the waveshape of a PD current pulse, focusing on influences of the *fBW*. Especially, we were interested in how fast the rise time of PD current pulse could appear in SF_6 gas with the higher *fBW* measurement and how changes the PD current waveform depending on the *fBW* from the viewpoint of the understanding the source of PD-induced electromagnetic (EM) wave. This result could improve the sophistication of the UHF method as a diagnostic technique for the high-voltage gas-insulated power apparatus. Additionally, using these measured PD current waveforms, we discussed the time integral values of the current pulse, *i.e.,* the charge quantity *q*, and the relationship between a PD current pulse and the induced EM wave.

1 INTRODUCTION

Measurement of partial discharge (PD) signals is one of powerful methods of insulation diagnosis for high-voltage power apparatuses such as gas-insulated switchgear (GIS), power transformer, power cable and so on. As a PD signal, PD-induced electromagnetic (EM) wave with an ultra high frequency (UHF) band component is one of popular and attractive signals due to a number of practical advantages that provide the non-contact, higher sensitive and faster response insulation diagnostic technique known as the UHF method.

So far, there have been a number of studies on the UHF method as well as PD phenomena [1]. PD current waveform is very significant because it has key information on PD phenomena and is a source of EM wave for the radio frequency (RF) diagnostic techniques including the UHF method. As for the PD current measurement, A.J. Reid, et al. [2,3] have constructed an excellent test setup with an extremely wider frequency bandwidth (13GHz) measurement system. They showed that the minimum rise time of PD current pulse measured in SF_6 gas was 35ps and the amplitude or energy of RF signals radiated from a PD source is strongly dependent on the rate of charge of PD current pulse. However, performance of the measurement instruments, especially a digital oscilloscope, is now further improved. So, using these improved instruments, we tried to construct a much more sophisticated measurement system by expanding the frequency bandwidth up to the super high frequency (SHF) band whose range is 3GHz to 30GHz. This system could contribute to address the heart of the PD phenomena in SF_6 gas, and consequently the sophistication of diagnosis technique on the PD-induced EM wave based on the deeply understanding the PD phenomena.

In this study, focusing on the frequency bandwidth dependence of PD current waveforms, we investigated PD current pulses in SF_6 gas with a sophisticated super high frequency wide band measurement system, *i.e.,* the SHF_PDPW system. Additionally, we discussed the time integral values of the current pulse, *i.e.,* the charge quantity *q*, and the relationship between a PD current pulse and the PD-induced EM wave.

2 EXPERIMENTAL SETUP AND PROCEDURES

2.1 SHF_PDPW system for PD current pulse and the induced EM wave measurement

Figure 1 shows the experimental setup of a super high frequency (SHF) wideband measurement system (SHF_PDPW system) to precisely measure the waveform of a PD current pulse in a gaseous insulation media. Basically, the construction of this system is the same as the extremely wide bandwidth (13GHz) measurement system previously constructed by A.J. Reid, et al [2,3], but the frequency bandwidth of this system including the used digital oscilloscope was much higher than that. Namely, the SHF_PDPW system could measure the PD current waveform up to 20GHz or 26.5GHz, which is limited by the frequency bandwidth of the used oscilloscope and attenuator.

The SHF_PDPW system mainly consists of a test cell to generate PDs, a matched low loss transmission line with a 40GHz coaxial cable and a 6dB attenuator calibrated up to 26.5GHz, and a 32GHz digital oscilloscope (Agilent technology, DSOX/DSAX 93204A, 32GHz, 80GS/s, trosc = 12.5ps) or a 20GHz digital oscilloscope (Tektronix, DPO/DSA/MSO 72004C, 20GHz, 100GS/s, trosc = 18ps). The test cell consists of a plane to a specially arranged needle electrode system that was directly attached to a SMK type connector with a stainless cylinder specially designed as a 50Ω coaxial line with the needle, and a non-metallic casing for containing pressurised SF_6 gas and measuring the PD-induced EM wave outside the casing.

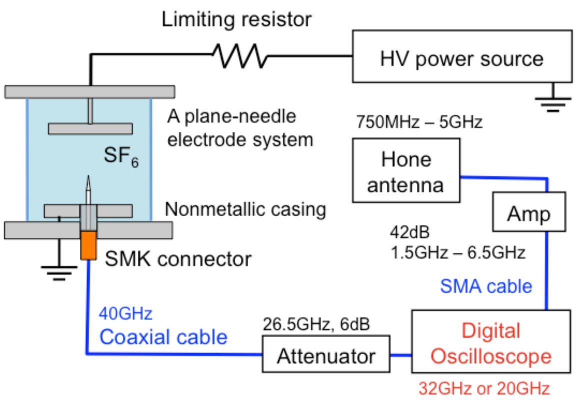


Figure 1: Experimental setup to precisely measure the waveform of PD current pulse in SF_6 gas with the SHF_PDPW system.

2.2 Measurements

High voltage is applied to an upper plane electrode to generate PDs. A lower needle electrode becomes ground potential due to the configuration. Thus, for example, when the applied voltage polarity was a negative one, PDs generated at the tip of the needle electrode became a positive corona, then the measured PD current waveform was a negative pulse, and vice versa. In order to avoid any confusion in the polarity of corona and PD current waveform, we inverted the PD current waveform to agree with the corona polarity.

In this study, we used two needle electrodes with the different lengths as l = 9.6mm and 19.6mm whose gap length to the plane electrode were not same as 24.7mm and 35.0mm, respectively. We investigated PD current waveforms varying with the SF_6 gas pressure from 0.1 to 0.3MPa and applied voltage. The PD-induced EM wave is also measured simultaneously with the PD current waveform with a Hone antenna (Schwarzbeck, BBHA9120A) whose frequency band is 750MHz to 5GHz, and an amplifier with 42dB.

3 EXPERIMETAL RESULTS

3.1 PD current waveforms measured by different frequency bandwidth *fBW*

As a typical example, Figures 2(a) to (f) show the PD current waveforms with different frequency bandwidth *fBW* from 32GHz to 1GHz of the used oscilloscope under the same experimental condition (Negative corona). Namely, each figure was measured individually with different *fBW*s. As shown in this figure, when the *fBW* was decreased from 32GHz (Figure 2(a)) to 1GHz (Figure 2(f)), the PD current waveform was clearly changed depending on the *fBW*. The peak value *Ip* and the rise time (10%-90%) *tr* of the PD current waveform decreased and the pulse width *tw* increased with a decrease in *fBW*. Also, it could be similarly confirmed that the PD current waveform depended on the needle length and a part of small peaks was formed by the reflection of the electrode [2,3].

Figure 3 indicated the *fBW* dependences of the *Ip* and the *tr* for the negative corona current pulses under different test conditions. Note that plots of the *Ip* correspond to the average value and the *tr* the minimum one. Also, Figure 3 was normalized result by the value at *fBW* = 32GHz. From Figure 3, the normalized property of both *Ip* and *tr* measured under different test conditions showed a similar property. As *fBW* decreased, *Ip* decreased and *tr* increased remarkably below *fBW*=10GHz. Comparing the values at *fBW*=1GHz with those at *fBW*=32GHz, *Ip* decreased by from 70% to 82% and *tr* increased by from 4.7 to 10.9 times. The minimum *tr* observed in this study was 22.3ps.

Here, we considered the relationship between the peak value *Ip* and the charge quantity *q* obtained by the time integral of the waveform. As shown in Figure 4, the relationship between *Ip* and *q* of a PD current pulse differed depending on the *fBW*. This figure suggests that when we treat the PD current pulse with the same *Ip*, the *q* could differ depending on the frequency bandwidth of the measurement system. The *q* measured with *fBW*=1GHz could be about 5 times greater than that at *fBW*=32GHz due to the wider pulse waveshape. The *fBW* dependence of *q* will be discussed further in the next chapter.

3.2 PD current waveforms processed by a function of the bandlimiting filter of the oscilloscope

We carried out the waveform processing of the measured PD current waveform with a function of the bandlimiting filter of the oscilloscope. Namely, using the one PD current waveform measured by the maximum *fBW*, we applied the bandlimiting

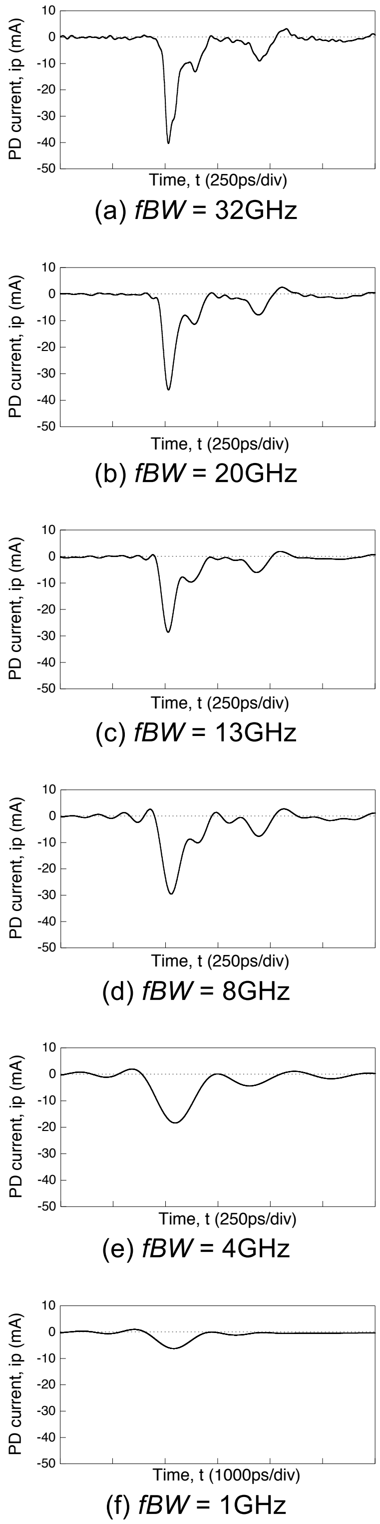


Figure 2: PD current waveforms in SF_6 gas measured with different frequency bandwidth *fBW* of the used oscilloscope (l=9.6mm, P=0.3MPa, negative corona).

filter to it. Hereafter, we referred to the frequency band of the bandlimiting filter as *fBWwp*. As a typical example, Figure 5(a) shows the original measured PD current waveform with *fBW*=20GHz (positive corona), and Figures 5(b) to (e) show the processed waveforms with from *fBWwp*=13GHz to 1GHz, respectively. With higher *fBW* measurement,

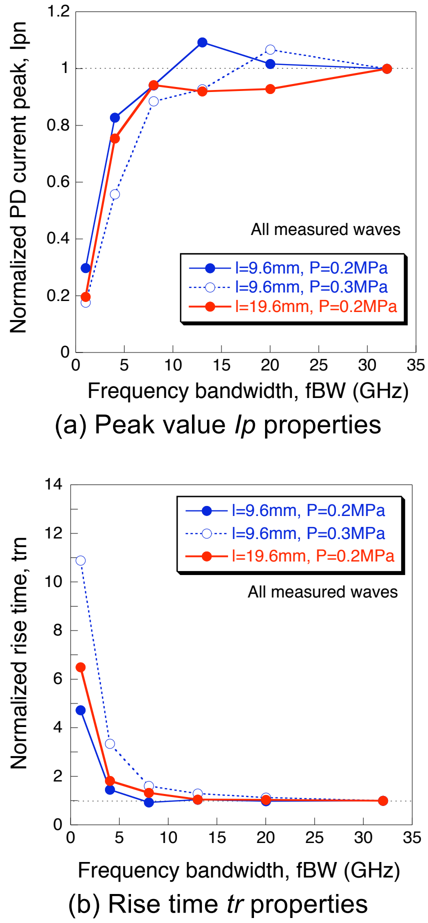


Figure 3: *fBW* dependences of normalized *Ip* and *tr* of the measured PD current waveforms by the value at *fBW* =32GHz (negative corona).

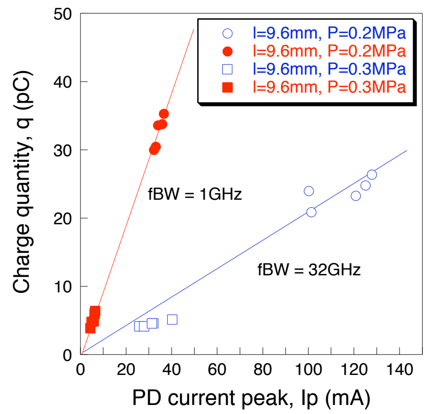
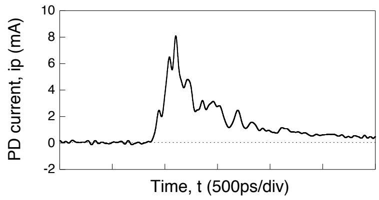


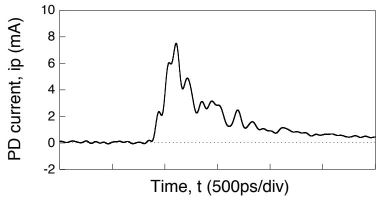
Figure 4: Relationship between *Ip* and *q* of PD current waveforms measured with different frequency bandwidth *fBW* under different conditions (negative corona).

the PD current waveforms of positive corona as shown in Figure 5 differed from those of negative corona as shown in Figure 2. Note that the time scale of Figures 2 and 5 is completely different. As shown in Figure 5, a PD current pulse for the positive corona had multiple peaks, smaller *Ip* and wider pulse width as compared with that for the negative corona.

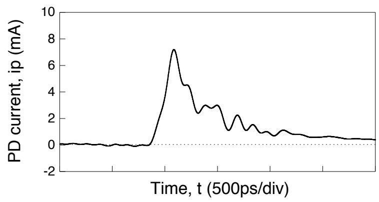
To make influences of the frequency bandwidth on the measured PD current waveform clear, we showed the original measured waveform with *fBW*=20GHz together with the processed one with *fBWwp*=1GHz in Figure 6. From Figure 6, it implies that we should take due account of the importance of the frequency bandwidth *fBW* of the PD current pulse measurement system because if the *fBW* is not sufficient for PD phenomena, significant waveshape information such as multiple peaks, peak value, rise time and so on could disappear.



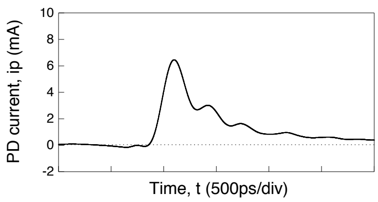
(a) *fBW* = 20GHz (measured pulse)



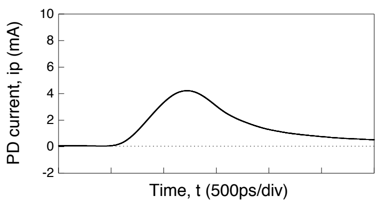
(b) *fBWwp* = 13GHz



(c) *fBWwp* = 8GHz

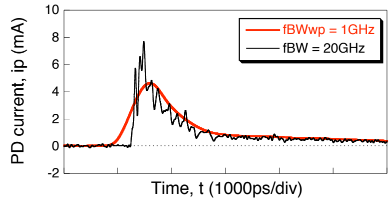


(d) *fBWwp* = 4GHz

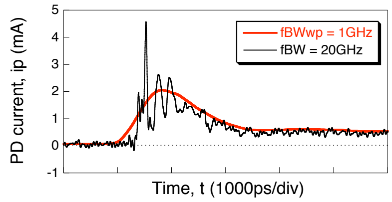


(e) *fBWwp* = 1GHz

Figure 5: PD current waveforms processed by a function of the bandlimiting filter of the oscilloscope with the waveform processing frequency bandwidth *fBWwp* (l=9.6mm, P=0.3MPa, positive corona).



(a) *l*=9.6mm, P=0.2MPa



(b) *l*=19.6mm, P=0.2MPa

Figure 6: Typical examples of relationship between the measured PD current waveform with *fWB*=20GHz and the processed one with *fBWwp* = 1GHz at different conditions (positive corona).

Figure 7 shows the *fBWwp* dependence of the normalized Ip of the processed PD current waveforms for the positive corona by the value at *fBW*=20GHz. Since it was difficult to define the tr due to the multiple peaks, tr properties could not be discussed here. Similarly in Figure 7, as shown in Figure 3, *Ip* decreased with a decrease in *fBWwp* even though the dependence of the needle length was found. This dependency may be attributed to the difference in waveshape as shown in Figure 6.

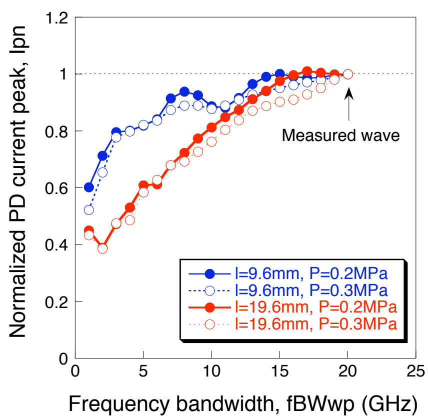


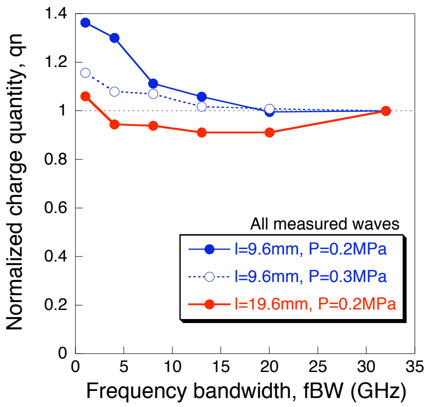
Figure 7: *fBWwp* dependence of normalized *Ip* of the processed PD current waveforms by the value at *fBW* =20GHz (positive corona).

4 DISCUSSIONS

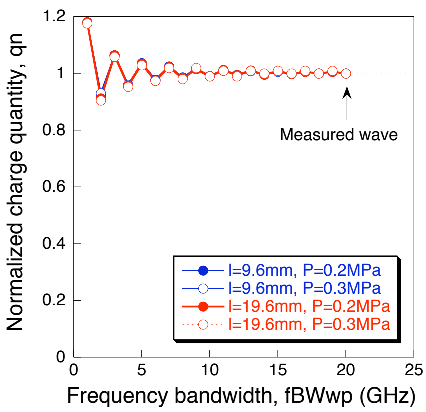
4.1 Influences of frequency bandwidth on the measured PD current pulse

As quantitatively shown in Figures 3 and 7, PD current waveforms depended on the frequency bandwidth of the measurement system. Here, we further investigated the *fBW* or *fBWwp* dependences of the time integral of PD current waveform that corresponds to a charge quantity q. From Figures 8 (a) and (b), the charge quantity q seems to increase with a decrease in the frequency bandwidth. Comparing the q at *fBW* = 1GHz or *fBWwp*=1GHz with that at the each maximum *fBW* = 32 or 20 GHz respectively, q increased by from 1.1 to 1.36 times. The oscillation of q in Figure 8(b) may be caused by the properties of the bandlimiting filter applying the same pulse.

Figure 9 shows the relationship between the minimum rise time of the measured PD current pulses for negative corona (Figure 3(b)) and the measurement limit of the rise time of the used oscilloscope at each *fBW*. This figure gives the significant information on the measurement of the rise time of a PD current pulse with a steep front. Namely, in some cases, the measured *tr* below *fBW*=10GHz was limited by the finite step response of the oscilloscope, *trlim*. In view of the limitation by the *trlim* and the suppression of the ringing effect caused by the insufficient frequency bandwidth, *fBW* over 20GHz would be well suitable for the precise PD current pulse measurement.



(a) Measured waveform (negative corona)



(b) Processed waveforms (positive corona)

Figure 8: Frequency bandwidth dependence of the normalized charge quantities of the PD current waveforms by the value at the maximum *fBW*.

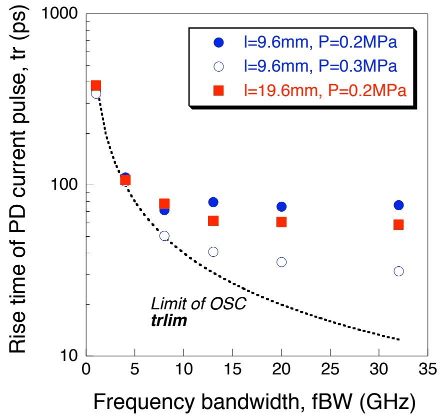


Figure 9: Relationship between the minimum rise time of the measured PD current pulses (Figure 3(b)) and the measurement limit of a rise time of the oscilloscope at each *fBW*.

4.2 Relationship between PD current waveform and PD-induced EM wave

As mentioned above, waveshape of a PD current pulse significantly differs depending on the *fBW*. Thus, to accurately measure a PD current pulse with a sufficient wider frequency bandwidth is important, which brings to a deeper understanding of PD phenomena as well as the input data for the analysis of emission and propagation properties of ME wave by a simulation of electrical transients like FD-TD method as a generation source (Figure 10). The deeper understanding of PD phenomena could also contribute to the sophistication of the insulation diagnosis. Note that as shown in Figure 10 we have to be careful when we discuss the relationship between PD current pulse and the measured PD-induced EM wave *Vem*, because the *Vem* could be affected by the properties of the measurement instruments.

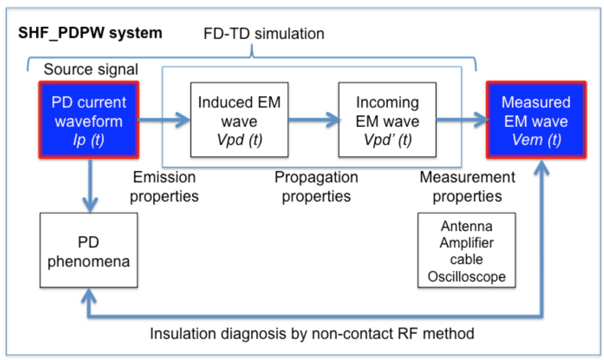
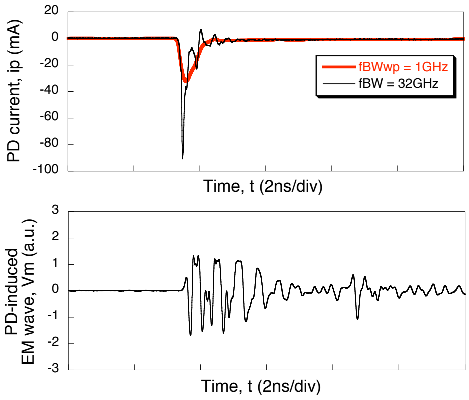
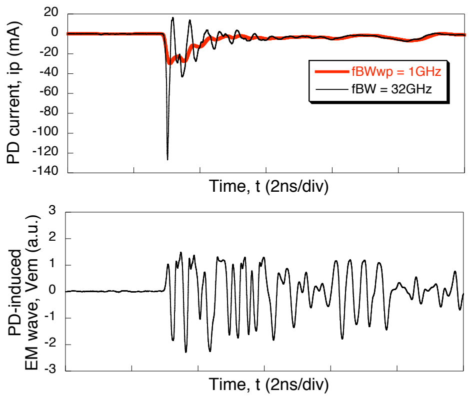


Figure 10: Schematic view of importance of the precise measurement of PD current pulse and the relation with the UHF method.

Finally, Figure 11 shows a typical example of a relationship of measured waveforms between a PD current pulse and the PD-induced EM wave, which are simultaneously measured in and outside of the test cell. The two PD current waveforms in the figure are the original measured PD current pulse with *fBW*=32GHz (black line) and the processed one with *fBWwp*=1GHz (red line), respectively. From Figure 11, it was found that the waveform of PD-induced EM wave seems to change in response to changes in PD current waveform at *fBW*=32GHz compared with that at *fBWwp* =1GHz. Theoretically, a peak value of the EM wave emitted from a small dipole at far field is proportional to the rate of change of current. In Figure 11, the relation was not completely satisfied even for the PD pulse at *fBW*=32GHz, because the measured EM wave also could be affected by the frequency bandwidth properties of the used measurement instruments such as the antenna, the amplifier, the cable and the oscilloscope as pointed out in Figure 10. So, we will further investigate the relationship between a PD current pulse and the measured EM wave by taking the frequency bandwidth property into account.



(a) l=9.6mm, P=0.2MPa



(b) l= 19.6mm, P=0.2MPa

Figure 11: Simultaneous measurement of PD current pulse and the induced EM wave at different test conditions.

5 CONCLUSIONS

In this paper, we investigated PD current waveforms in SF_6 gas with the sophisticated super high frequency wide band measurement system (SHF_PDPW system) with a 32GHz or 20GHz digital oscilloscope by changing the needle electrode length, gas pressure, applied voltage as the test conditions, as well as the frequency bandwidth *fBW* of the measurement system up to 32GHz. As a result, the waveshape of a PD current pulse significantly differed depending on the *fBW*. The *fBW* dependences of PD current waveshapes such as the peak value *Ip*, the rise time *tr* and the charge quantity *q* obtained by the time integral of the waveform were shown quantitatively. Also, the importance of the frequency bandwidth *fBW* of the PD current pulse measurement system was shown. This is because if the *fBW* is not sufficient for PD phenomena, significant waveshape information such as multiple peaks, peak value, rise time and so on could disappear. In view of the limitation by the finite step response of the oscilloscope and the suppression of the ringing effect caused by the insufficient frequency bandwidth, *fBW* over 20GHz would be well suitable for the precise PD current pulse measurement in SF_6 gas.

6 ACKNOWLEDGMENTS

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