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An UWB Printed Antenna for Partial Discharge UHF Detection in High Voltage Switchgears

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Abstract—As important fundamental equipment, high voltage switchgears are widely used in electric power systems and directly relative to the power reliability and quality. Partial discharge (PD) online monitoring is one of the most effective methods used for insulation testing and diagnosis in high voltage switchgears and power systems. This paper proposes a unique ultra-wide-band (UWB) antenna with high performance for PD ultra-high-frequency (UHF) detection in high voltage switchgears. Actual PD experiments were carried out, and the designed antenna was used for PD measurements. The measured results demonstrate that the proposed antenna has wide work frequency band, good omnidirectional radiation patterns and appreciable gain, which indicate that the proposed antenna is suitable for UHF online monitoring of PDs in high voltage switchgears.

1. INTRODUCTION

High voltage switchgears are widely used as important fundamental equipment in electric power systems, which are directly relative to the power reliability and quality [1]. Partial discharge (PD) as a potential threat directly affects the insulation safety in high voltage switchgears and power systems [2]. The PD signal contains abundant information of insulation states, and the ultra-high-frequency (UHF) method, as one of the most important detection methods, is widely used in inspecting insulation defects and fault diagnosis in electric equipment. Compared with other methods, such as ultrasonic detection [3, 4], radio frequency (RF) detection [5], and transient earth voltage detection [6], the UHF method has the advantages of high sensitivity and strong anti-interference ability, and it has extensive application prospects [7].

Compared with the antennas in communication systems [8, 9], the UHF antenna detects the electromagnetic waves in the frequency range from 300 MHz to 3 GHz [10]. Currently, different UHF antennas, which can be classified as external and built-in, are used for PD detection in transformers, gas-insulation switches (GIS), wind power devices, power cable and etc. [11–20]. However, the study on the UHF antenna for PD detection application in the high voltage switchgear is not enough, and those previous antennas either have narrow operating bandwidths or have low gain. Therefore, there has been growing interest in looking for a novel antenna with wide bandwidth and high gains, which is used for UHF PD online monitoring in high voltage switchgear.

In this paper, a UWB printed antenna for online monitoring of PDs in high voltage switchgears is proposed. This new antenna is developed based on the optimal design procedure. The voltage standing wave ratio (VSWR), 2D normalized radiation patterns and peak gain of the fabricated antenna are obtained through simulations and measurements. Besides, the performance of this proposed antenna for PD detection is tested through actual PD experiments.

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2. OPTIMAL DESIGN OF UWB PRINTED ANTENNA

2.1. Design Criteria of UWB Antenna for PD Detection

The performance of a UWB antenna determines the ability of PD UHF detection systems for high voltage equipment. Therefore, the design of a UWB antenna plays a crucial role to the accuracy and sensitivity of the PD UHF detection system, and different equipment has different requirements on UWB antenna. According to the structure and PD characteristics of the high voltage switchgears, the design criteria of UWB antenna for PD UHF detection in high voltage switchgears are described as follows:

(1) Normally, the frequency bands of electromagnetic interference signals in the electromagnetic environment of electrical equipment does not exceed 200 MHz. In order to avoid the electromagnetic interference, the work frequency of an antenna for PD detection should be in the UHF band (300 MHz $\sim$ 3 GHz) [21]. Considering the major concentrated frequency band of the PD energy, the lowest and highest resonant frequencies of an UWB antenna can approach 500 MHz and 1500 MHz, respectively [22].

(2) Due to the fast attenuation of electromagnetic wave in good conductors, the PD signals cannot penetrate the metal shell of the high voltage switchgears. Therefore, the built-in UWB antenna should be chosen for PD UHF detection in high voltage switchgears.

(3) The PD signals in high voltage switchgears are weaker and will have attenuation due to several refractions and reflections. So the UWB antenna should have a higher gain.

(4) In order to ensure that the PD signals in all directions can be received, the designed UWB antenna should achieve omnidirectional radiation patterns in H plane.

(5) For the built-in UWB antenna, it should have a reasonable size and shape so that it has no influence on insulation safety of the high voltage switchgears in operation.

2.2. Optimization of UWB Printed Antenna

Many designs of UWB printed antennas have already appeared in the state of art work. However, most concentrate on wireless technology which spans from 3.1 to 10.6 GHz frequency range [23–25]. This paper presents an expansion of the planar monopole antenna with rectangular patch.

Initially, the rectangular microstrip antenna is designed with the use of commercial software Ansoft HFSS, and the simulation model is shown in Figure 1. The radiator plane of length 88 mm (L_p) and width 110.5 mm (W_p) and ground plane of length 109 mm (L_g) and width 182 mm (W_0) are etched on the opposite sides of the dielectric substrate (in this study, an FR4 substrate of length 215 mm (L_0), width 182 mm (W_0), thickness 2 mm (H) and relative permittivity 4.4 was used). The radiator of this

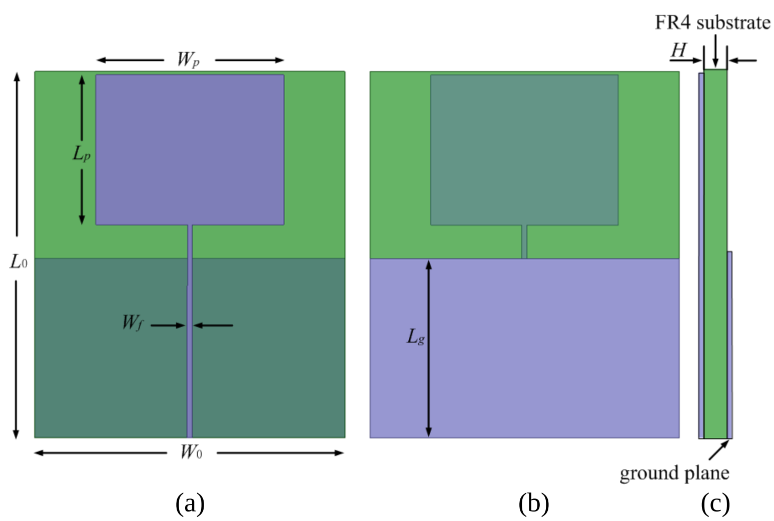

Figure 1. Simulation model of rectangular microstrip antenna. (a) Top view. (b) Back view. (c) Side view.

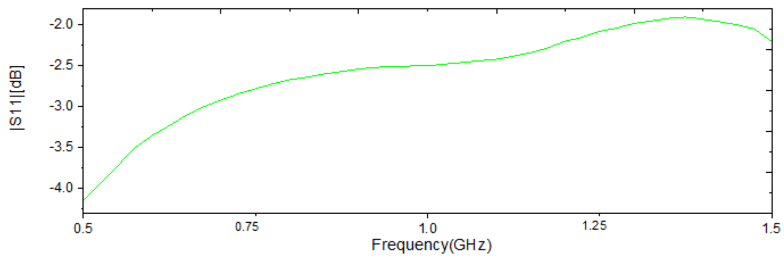

Figure 2. S_{11} curve of the rectangular microstrip antenna.

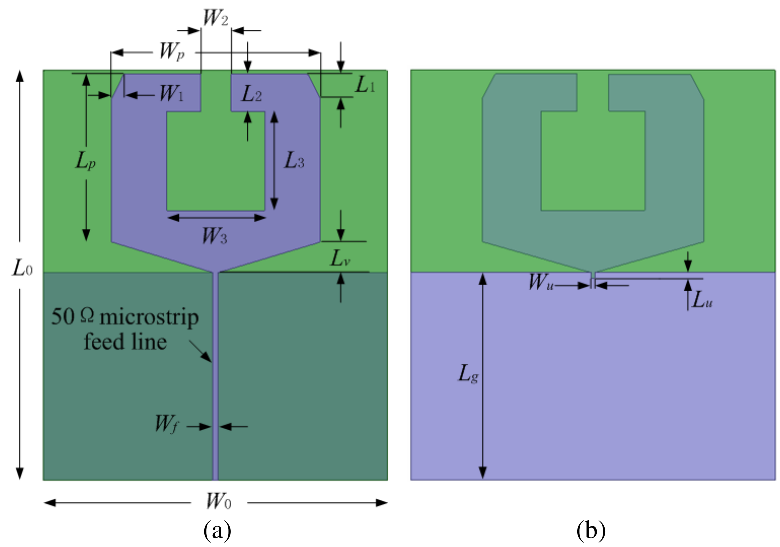

Figure 3. Schematic configuration of the proposed UWB printed antenna. (a) Top view. (b) Back view.

rectangular microstrip antenna is fed by a microstrip line of width 3 mm (W_f) to meet 50 Ω characteristic impedance.

Because the bandwidth performance of the rectangular microstrip antenna is far from enough to meet the design requirement of a UWB microstrip antenna, as shown in Figure 2, the structure optimization of the rectangular microstrip antenna is needed to be studied.

The schematic configuration of the proposed UWB printed antenna is shown in Figure 3. To possess a wider impedance bandwidth, in this paper a slanted structure at both sides of the radiating patch is developed to have a proper spacing to mitigate the effect caused by the circuit and casing, so good impedance matching across the operating bands for the antenna can be obtained [26]. In order to optimize the antenna dimensions, simulations are carried out using the 3-D full-wave software Ansoft HFSS.

The values of geometrical parameter L_v are optimized to enhance the antenna performance for practical application. The corresponding S-parameter ($|S_{11}|$) is shown in Figure 4. Compared with the planar monopole antenna with rectangular patch, it can be observed that a tapered structure between the radiating patch and the microstrip feed line is an effective way to improve the bandwidth performance. The value of parameter L_v is determined as 16 mm through comprehensive consideration. Similarly, the optimized simulations of parameters W_1, L_1, W_u and L_u can also be investigated.

In order to reduce the effective area of the radiating patch, here we also simulate the surface current distribution of the antenna at 1 GHz. As expected, the surface current shown in Figure 5 is mainly distributed along the microstrip feed line and at the bottom edge of the radiating patch. According to the electromagnetic theory, the radiating patch with lower current distribution has a little influence on the antenna performance. In this paper, an inverted T-shaped slot shown in Figure 3(a) is cut from the

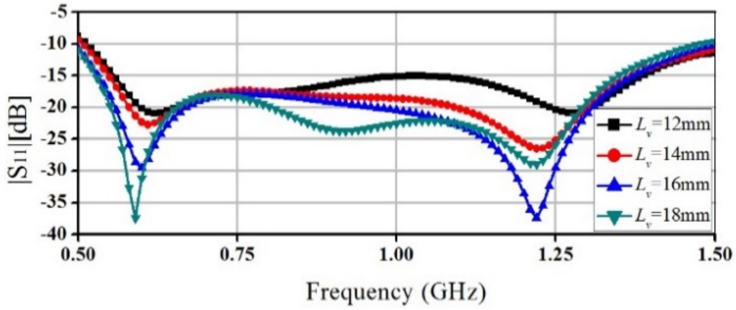

Figure 4. Simulated reflection coefficient of antenna with different values of geometrical parameter L_v.

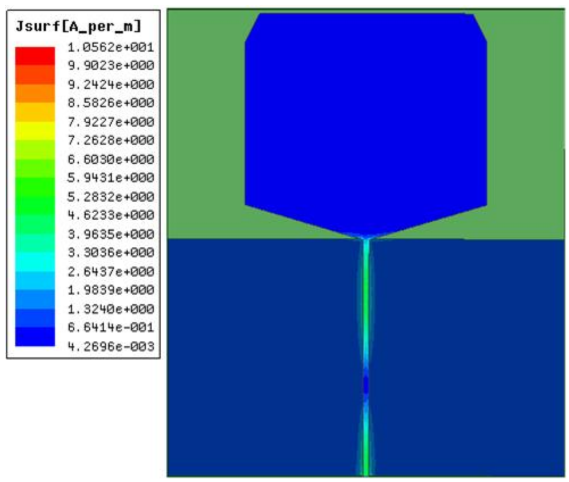

Figure 5. Simulated surface current distribution for the antenna at 1 GHz.

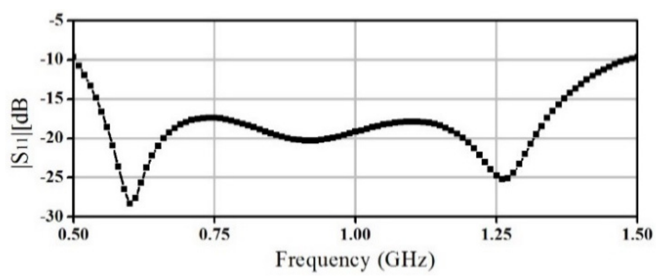

Figure 6. Simulated S_{11} of the proposed UWB printed antenna.

Table 1. Optimal geometrical parameters of the proposed antenna.

Parameter	W_0	L_0	H	W_f	L_f	W_p	L_p	L_g	W_u
Unit (mm)	182	215	2	3	109	110.5	88	109	2
Parameter	L_u	W_1	L_1	L_v	W_2	L_2	W_3	L_3	
Unit (mm)	3.2	6.5	13	16	16	19.5	52	52	

radiating patch to realize miniaturization.

Through the optimized simulations, the final antenna parameters are summarized in Table 1. According to these parameter values, the simulated S_{11} of the proposed UWB printed antenna is shown in Figure 6. It is indicated that the simulated -10 dB input matching bandwidth covers from 0.5 to

1.5 GHz, which satisfies the bandwidth performance criteria of UHF antenna for application in high voltage switchgear.

2.3. Fabrication and Measurement Results

Figure 7 shows pictures of the fabricated UWB printed antenna with dimensions as listed in Table 1. The feed port of the antenna is connected to the coaxial line of characteristic resistance 50 Ω through a coaxial SMA connector.

(a) (b)

Figure 7. Photographs of the fabricated UWB printed antenna. (a) Top view. (b) Back view.

The S_{11} parameter of the fabricated antenna has been measured with an Agilent Technologies E5071B programmable network analyzer, and the result curve is shown in Figure 8. Compared with the simulated curve, it can be found that the measured value of S_{11} in the low frequency band has a little difference, which is mainly caused by machining precision, SMA connector, testing environment or other factors. But in general, close agreement between the measured and simulated results of S_{11} is observed in the targeted frequency range, and the measured result shows that the work frequency can satisfy the bandwidth requirements for PD UHF detection in high voltage switchgear.

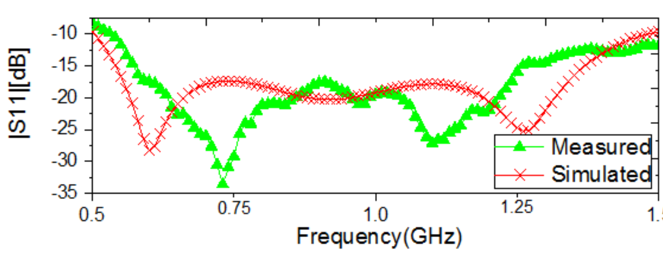

Figure 8. Measured and simulated S_{11} of the fabricated UWB printed antenna.

Figure 9 shows the measured 2D normalized radiation patterns of the fabricated antenna at 500, 750, 1000, 1250 and 1500 MHz. There is no significant difference for the radiation patterns over the wide frequency range. It can also be seen that the fabricated antenna has a good omnidirectional radiation pattern in the H-plane and a dipole-like radiation pattern in the E-plane. The measured peak gain of the fabricated UWB printed antenna for operating frequency within the range of 0.5 to 1.5 GHz bandwidth is shown in Figure 10. It is observed that the measured antenna peak gain is about 1.1 to 3.5 dB with an average value of 2.32 dB. From the measured results of the radiation patterns and peak gain, it can be concluded that the performance of the fabricated antenna meets the design criteria of an UHF antenna for PD detection in high voltage switchgear perfectly.

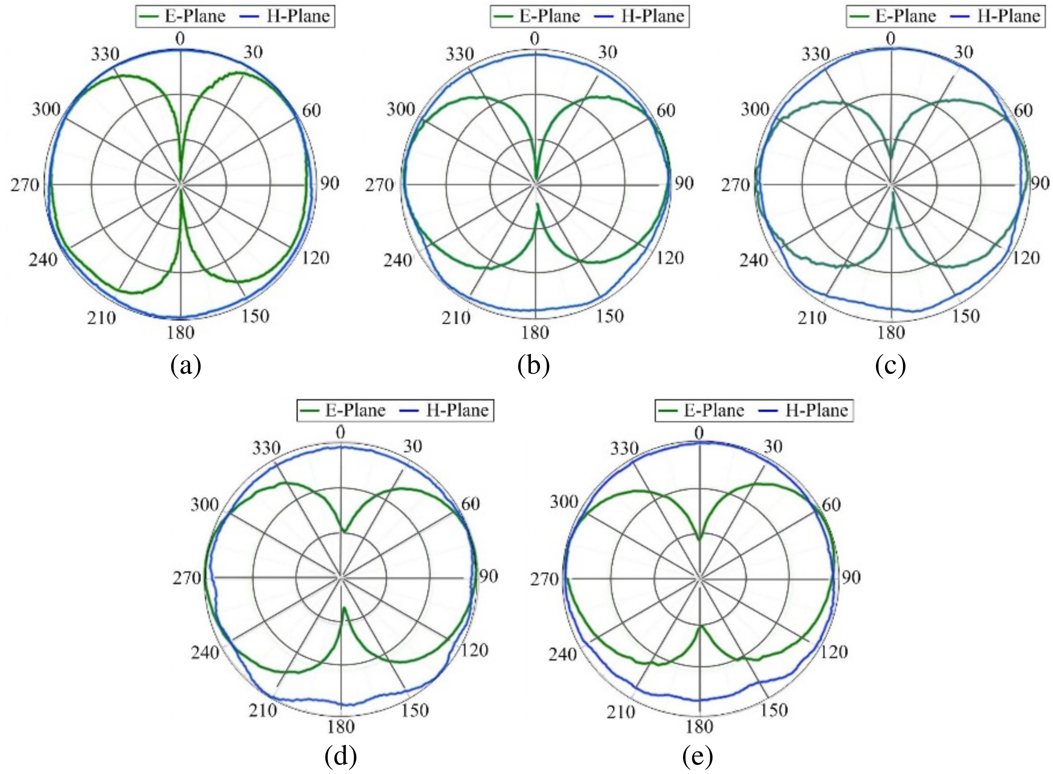

Figure 9. Measured 2D normalized radiation patterns of the fabricated antenna at several different frequencies. (a) 500 MHz. (b) 750 MHz. (c) 1000 MHz. (d) 1250 MHz. (e) 1500 MHz.

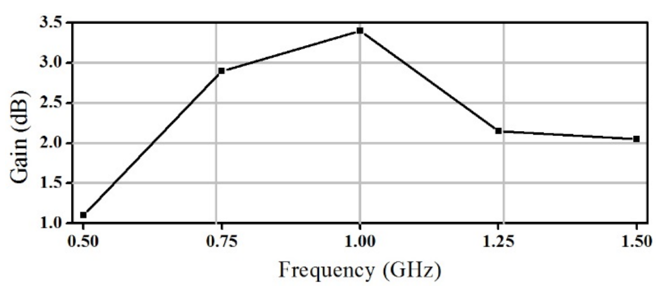

Figure 10. Measured peak gain of the fabricated UWB printed antenna.

3. PARTIAL DISCHARGE EXPERIMENTS AND RESULTS

3.1. Laboratory Test

Figure 11 shows the experimental setup of the PD UHF detection.

The designed UHF antenna is located in the vicinity of the testing model, and distance between the test and antenna is set 50 cm. In this paper, only the air cavity discharge model is taken for an example, and this model consists of three layers of insulation dielectric plates and a cylinder-to-board electrode system. The output signal of the antenna is transferred into an oscilloscope with the maximum sampling frequency 20 GS/s through a band-pass filter and an amplifier. The experiment is carried out in an electromagnetic shielded laboratory.

When high voltage is applied to the insulation dielectric plates, the electric field will be greater inside the air cavity than in the dielectric plates, and most of internal PDs will occur in that region. A

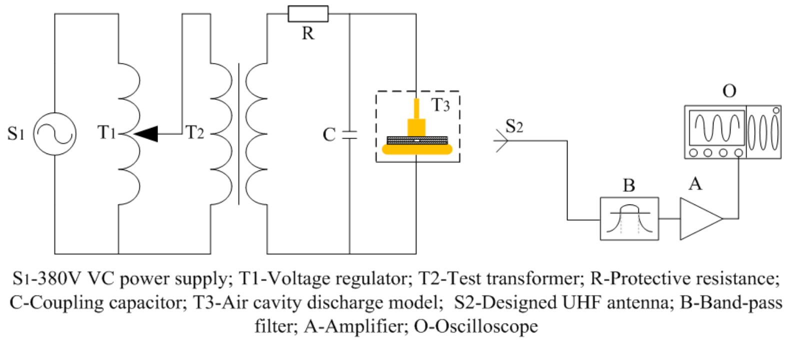

Figure 11. The setup of PD experiment in laboratory.

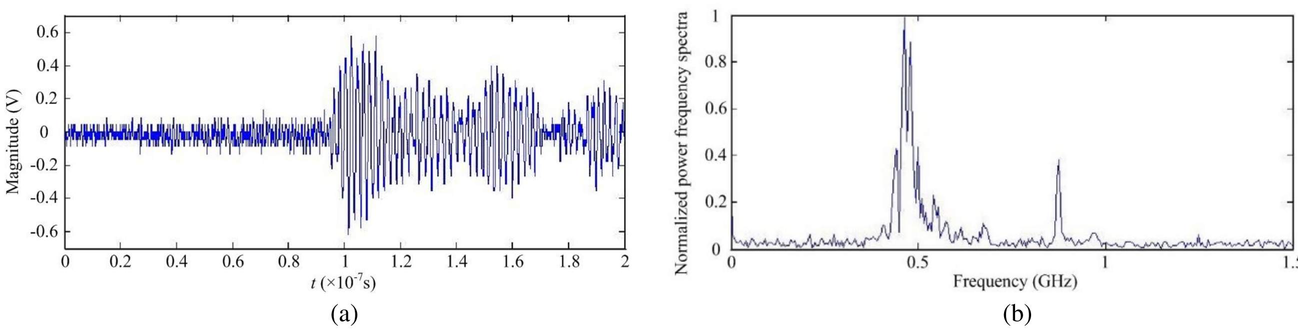

Figure 12. Detection results of PD UHF signals from air cavity discharge model. (a) Time-domain waveform. (b) Normalized power frequency spectra.

time-domain waveform in a time window of 200 ns at 9.7 kV and the corresponding normalized power frequency spectra of PD UHF signal are shown in Figure 12(a) and Figure 12(b), respectively. The characteristics of detection results are generally in good agreement with reported studies on similar PD defect [27]. Hence, it can be concluded that the designed UHF antenna is effective in detecting PD waveforms, and the PD UHF signals can be used for recognition by analysis to the waveforms.

3.2. On-Site Test

On-site PD measurements are made on high voltage switchgears. An example of such a measurement in Chuankai Electric Co., Ltd. is given in Figure 13. The two antennas are located at a distance of 0.75 m from the test switchgear to test the insulation performance of the switchgear (specification JYN1-27.5). The voltage loaded on the switchgear is 110 kV. The process of on-site test is 2 minutes (at least 1minte withstand 110 kV). PD information obtained using the two detection systems is combined to give a comparison between the proposed UWB printed antenna and an existing straight wire monopole antenna.

During the withstand voltage test process of the high voltage switchgear, the discharge waveforms and discharge quantities changing with the time are recorded by the monitoring terminals, as shown in Figure 14. It can be observed that the discharge quantity-time curves detected by the two antenna sensors have the same trend of variability, but the discharge quantity magnitude of the proposed UWB printed antenna is about 3.5 times as great as that of the existing straight wire monopole antenna [28]. For example, the magnitudes are 9427 pC and 2849 pC at 40 seconds. In other words, the proposed UWB printed antenna gets much better detection results due to its wider frequency band and higher gain.

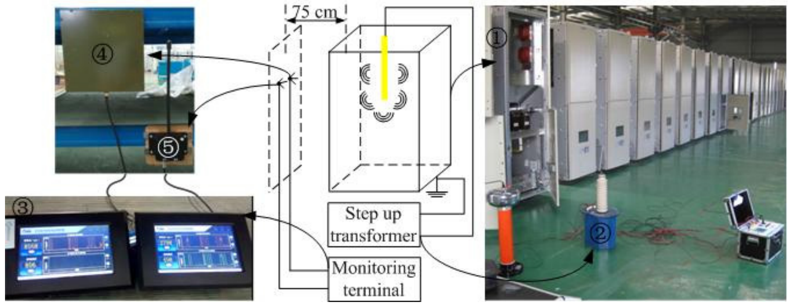

Figure 13. The on-site test setup of the high voltage switchgear used to measure PD with the two antennas: ①-test switchgear; ②-step up transformer; ③-on-site monitoring terminal; ④-proposed UWB printed antenna; ⑤-straight wire monopole antenna.

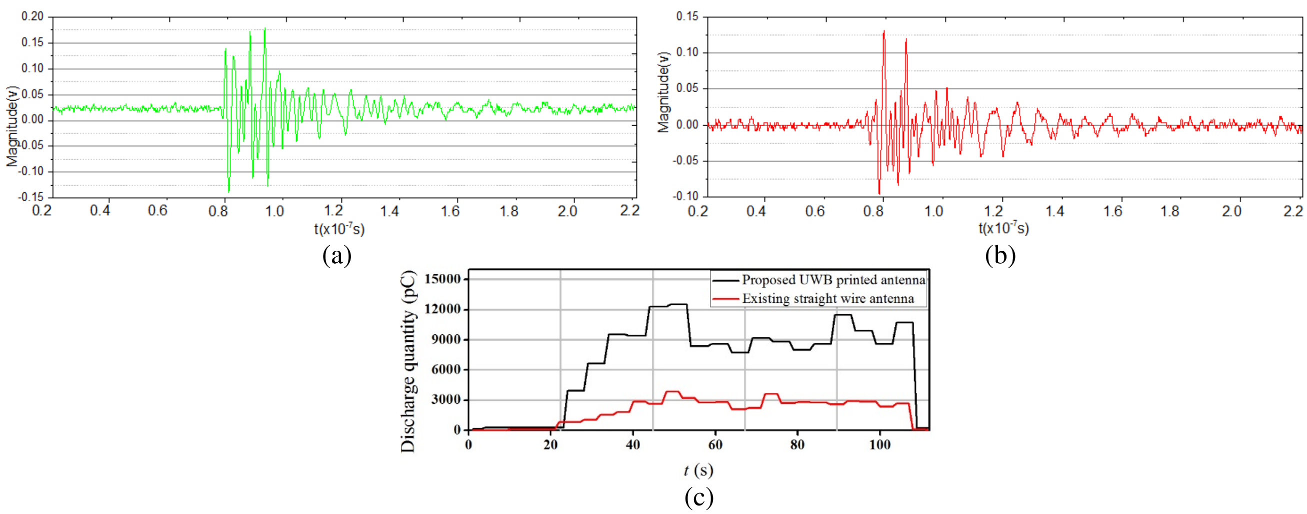

Figure 14. Discharge monitoring results. (a) Waveform detected in UWB printed antenna, (b) straight wire monopole antenna, (c) measured discharge quantity curves against time using the two antennas.

4. CONCLUSION

In this paper, a UWB printed antenna for PD UHF detection in high voltage switchgears is presented. The design of the antenna is optimized through simulation studies. Measurement results of the fabricated antenna show that the work frequency of the UWB printed antenna band has a little difference between the simulation and measurement. The proposed UWB printed antenna has a good omnidirectional radiation pattern in the H-plane, and the peak gain variation is about 1.1 to 3.5 dB with an average value of 2.32 dB. Moreover, the actual PD experiments were carried out to verify the good performance of the proposed antenna. For these reasons, the proposed UWB printed antenna is well suited for PD UHF online monitoring of high voltage switchgear.

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