Partial Discharge Localization through a UHF Signal Amplitude Strength Attenuation Approach

Tingbo Jia¹, Nan Zheng¹, Anqing Sun¹, Peng Li¹, Qichen Yu² and Lingen Luo²

¹ Rizhao Power Supply Company, Shandong Electric Power Corporation, Rizhao, China
² Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China

Corresponding author’s e-mail: llg523@sjtu.edu.cn

Abstract. Accurate measurement and localization of Partial Discharge (PD) is necessary for safe and stable operation of power equipment. Recently, the method based on the amplitude strength of Ultra High Frequency (UHF) signals has been proposed that bearing a low hardware requirement compared to time-difference-based methods. However, the widely studied fingerprinting based positioning technology is hard to deployed due to a heavy burden of fingerprinting map building. Therefore, this paper proposes an amplitude strength attenuation model and localization equation is proposed for PD localization in air-insulated substation. The field test is performed and the results show that the mean PD source localization error is 2.51 meters which is enough to distinguish the power equipment that having insulation deterioration.

1. Introduction

Partial discharge (PD) in high-voltage electrical equipment will lead to a reduction in insulation performance and is one of the important causes of major accidents in electrical equipment [1]-[3]. Partial discharge detection of power equipment can verify the insulation failure and reduce the probability of accidents which makes it necessary to apply accurate measurement and localization of Partial Discharge for safe and stable operation of the system.

Nowadays, the Ultra High Frequency (UHF) method is widely used in the detection of partial discharge of equipment [4]-[7], which is mainly based on Time of Arrival (TOA) or Time Difference of Arrival (TDOA) [8]. The TOA method calculates the distance according to the time and speed of transmission and reception of the signal, demanding accurate synchronization, while the time difference is used to calculate the distance in TDOA method by transmitting two signals of different speeds. Both TOA and TDOA methods use the delay of the signal for positioning, bearing high requirements for the hardware and the high-speed synchronize sampling support [9]. Taking that into consideration, some scholars attempt to use methods based on the Received Signal Strength Indicator (RSSI) to achieve localization, which can be divided into two categories, a ranging method based on signal attenuation model and a scenario analysis method based on fingerprint. RSSI fingerprint positioning technology needs to establish a feature information on geographic location information and RSSI, including offline and online stages that makes it complicated to implement.
Therefore, this paper proposes an amplitude strength attenuation model is proposed for PD localization in air-insulated substation. The results of field measurement indicate that the mean PD source localization error is 2.51 meters.

The rest of the paper is organized as follows. In section II, we introduce the basic principle of the PD localization by UHF amplitude attenuation, both attenuation model and localization equation are introduced. Section III gives a laboratory test for verification and corresponding results. And section VI concludes the paper.

2. PD Localization Based on the Amplitude Strength Attenuation of UHF Signal

2.1. Propagation Characteristics of Radiated Electromagnetic Field in Partial Discharge

The high voltage generated by PD source may cause the charge to move between the electrodes. Therefore, the current source antenna radiation model can be used to simulate the process of PD radiated electromagnetic field as shown in Fig. 1.

![Radiation electromagnetic field model of PD.](Image)

Supposing There is a current element with current $I$ and length $l$ at point O in Fig. 1. According to the theory of electromagnetic fields, for the point Q with a distance of $R$ to the current cell O, the magnetic field strength along the $\phi$ direction at point Q could be expressed as:

$$
H_{\phi} = a_{\phi} \frac{II}{4\pi} \sin \theta (\frac{jkR}{R^2} + \frac{1}{R}) e^{-j\phi R}
$$

(1)

The electric field strength at point Q has $R$ direction and $\theta$ direction, which are respectively expressed as:

$$
E_R = a_R \frac{\eta_0 II}{2\pi R^2} \cos \theta (1 + \frac{1}{jkR}) e^{-j\phi R}
$$

(2)

$$
E_\theta = a_\theta j \frac{\eta_0 II}{4\pi R} \sin \theta (1 + \frac{1}{jkR} - \frac{1}{k^2 R^2}) e^{-j\phi R}
$$

(3)

where $a_\theta$, $a_R$ and $a_\phi$ represent the unit vectors of three directions in the coordinate system shown in Fig. 1 respectively. $k$ is wave number which could be denoted as $k = \omega \sqrt{\varepsilon \mu}$, where $\omega$, $\varepsilon$, $\mu$ are current angular frequency, dielectric permittivity, and permeability respectively. Since $\varepsilon$ and $\mu$ are all 1 in the air, so $k = \omega = 2\pi / \lambda$. $\eta_0$ is the intrinsic impedance in vacuum, and $e^{-j\phi R}$ represents the phase difference between point Q and O.

Because the pulse current wave front time of PD is usually in nanoseconds, the wavelength of electromagnetic waves generated by PD is about several tens of centimeters. However, the UHF
sensors location are generally far from the PD source, which means $R \gg \lambda/2\pi$. Therefore, we can omit the $1/R^2$ and $1/R^3$ in (1) to (3), then:

$$H_y = \alpha_y I / 2\pi R \sin \theta e^{-j\lambda R}$$  \hspace{1cm} (4)

$$E_\phi = \alpha_\phi I / 2\pi R \sin \theta e^{-j\lambda R}$$  \hspace{1cm} (5)

Then we have:

$$|E_\phi| = \eta_0 |I| / 2\pi R \sin \theta = \frac{M_1 \sin \theta}{R}$$  \hspace{1cm} (6)

where $M_1$ is a constant and only related to the current cell O.

Supposing a PD happens, then the incident electric field strength of UHF antenna is denoted as $E$, and Magnetic field strength is denoted as $H$, then the power density $S$ at this point can be expressed as:

$$S = \frac{|E \times H^*|^2}{2}$$  \hspace{1cm} (7)

From (4), (5) and (7) we have:

$$S = \frac{|E_\phi|^2}{2\eta_0}$$  \hspace{1cm} (8)

The antenna effective area denoted as $A$ is expressed as:

$$A = \frac{G\lambda^2}{4\pi}$$  \hspace{1cm} (9)

where $G$ is the antenna gain.

From (8) and (9), the received power of the antenna could be written as:

$$P = SA = \frac{G\lambda^2 |E_\phi|^2}{8\pi\eta_0}$$  \hspace{1cm} (10)

Let the characteristic impedance of the antenna be $Z$, and the voltage amplitude of the antenna output, that is, the signal amplitude $U$, then we have:

$$P = \frac{U^2}{Z}$$  \hspace{1cm} (11)

From (10) and (11) we have:

$$U = M_2 |E_\phi|$$  \hspace{1cm} (12)

where $M_2$ is a constant and only related to the used antenna.

From equation (6) and (12) we have:

$$U = M_1 M_2 \frac{\sin \theta}{R}$$  \hspace{1cm} (13)

Equation (13) is the main conclusion of the relation between dense distance and amplitude strength. It worthy to denoted that, the PD location ($\theta$ and $R$) is only related to the amplitude value ($U$).

2.2. PD Source Localization Equation Based on UHF Amplitude Strength
To deduce the PD source localization equation based on UHF amplitude value as shown in Fig. 2, we suppose there is a PD source at point O and a UHF antenna at point $Q_i$.

Then we have:

$$\sin \theta_i = \frac{OQ'}{OQ} = \frac{Q'O'}{R_i} \quad (14)$$

Let the coordinate of point O is $(x, y, z)$, and the coordinate of point $Q_i$ is $(x_i, y_i, z_i)$, then:

$$\sin \theta_i = \frac{\sqrt{(x-x_i)^2 + (y-y_i)^2}}{R_i} \quad (15)$$

Therefore, if four UHF sensors are used, i.e., $i=1,2,3,4$. From (13) we have:

$$\begin{align*}
\sin \theta_1 & = \frac{U_1}{R_1} \sin \theta_1 \\
\sin \theta_2 & = \frac{U_2}{R_2} \sin \theta_1 \\
\sin \theta_3 & = \frac{U_3}{R_3} \sin \theta_1 \\
\sin \theta_4 & = \frac{U_4}{R_4} \sin \theta_1 \\
\end{align*} \quad (16)$$

The coordinate of PD source could be obtained by solving (15) and (16). The PD source localization equations are non-linear and could be solved by the Newton iteration method.

3. Experimental Verification

3.1. Experiment Setup

The experiment is performed using our designed wireless UHF sensors whose detail technical parameters are: the antenna bandwidth is 300MHz-1500MHz, the UHF RSSI value is obtained after signal conditioning by the bandpass filter, amplifier and peak detector, the A/D sampling rate is 2.7MHz and the sampled RSSI values are transmitted to computer through a Wi-Fi module controlled by MCU.

The mechanical structure of designed wireless UHF sensor is shown in Fig. 3 (a). To better effect of PD detection in substation, an omnidirectional PD antenna is designed and its sensitivity curve is reported in Fig. 3 (b).
Figure 3. Mechanical structure of wireless UHF sensor and sensitivity of PD antenna.

An experiment to study the PD source localization is performed as shown in Fig. 4. The test site is a square with 20*20 meters. Four wireless UHF sensors are placed at each vertex. The PD simulator is located at the center of the square area.

Figure 4. The plan and picture of laboratory experiment for PD source localization.

The experiment process is described simply as following: the wireless UHF sensor is fixed at a fix point, then the distance between the simulated partial discharge source and sensor is gradually changed in a straight line, and an air discharge pulse according to EN/IEC 61000-4-2 is generated by the PD simulator named “EM TEST DITO” [10], finally, the raw RSSI measurements at each position are collected. The parameters of PD simulator are set as: the inception voltage is 2kV, the rise time is 0.7ns and the spectrum is 0-1.5GHz. The collected PD UHF signal snapshot in 1 second known as PRPS picture is shown in Fig. 5.

Figure 5. Raw measurement snapshot in 1 second.
Total 1540 data are collected for verification and the PD localization results are reported in Table 1.

**Table 1. Results of PD Source Localization in Laboratory Experiment**

| Parameters                          | Results |
|-------------------------------------|---------|
| Average error/m                     | 2.51    |
| Maximum error/m                     | 3.7     |
| The proportion of the error that less than 2m | 47.6%   |

We can see that the average error of proposed localization algorithm is 2.51m, which is sufficient to identify the power equipment that having insulation deterioration in a substation.

### 4. Conclusion

Future smart substation requires an intelligent and low-cost fault early warning system for comprehensive insulation deterioration motoring of power equipment. This paper proposed a PD source localization method based on UHF amplitude strength attenuation model. A rigorous PD source localization equation is derived. The localization accuracy of proposed method is verified by laboratory test. The proposed method is also easier to deployed and more scalable than the RSSI fingerprinting based PD source localization method.

### References

[1] R. Schwarz, T. Judendorfer and M. Muhr, “Review of Partial Discharge Monitoring techniques used in High Voltage Equipment,” presented at Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 2008, pp. 400-403.

[2] A. S. Kumar, R. P. Gupta, K. Udayakumar and A. Venkatasami, “Online partial discharge detection and location techniques for condition monitoring of power transformers: A review,” present at International Conference on Condition Monitoring and Diagnosis (CMD), 2008, pp. 927-931.

[3] High-Voltage Test Techniques: Partial Discharge Measurements, Standard IEC 60270, 2000.

[4] P. J. Moore, I. E. Portugues, and I. A. Glover, “Radiometric location of partial discharge sources on energized high-voltage plant,” IEEE Transactions on Power Delivery, vol. 20, no. 3, pp. 2264–2272, 2005.

[5] I. E. Portugues, P. J. Moore, I. A. Glover, Ian A. Glover, C. Johnstone, R. H. McKosky, M. B. Goff and L. van der Zel, “RF-based partial discharge early warning system for air-insulated substations,” IEEE Transactions on Power Delivery, vol. 24, no. 1, pp. 20-29, 2009.

[6] Huijuan Hou, Gehao Sheng, Xiuchen Jiang, “Robust Time Delay Estimation Method for Locating UHF Signals of Partial Discharge in Substation,” IEEE Transactions on Power Delivery, vol. 28, no. 3, pp. 1960-1968, 2013.

[7] M. X. Zhu, Y. B. Wang, Q. Liu, J. N. Zhang, J. B. Deng, G. J. Zhang, X. J. Shao and W. L. He, “Localization of multiple partial discharge sources in air-insulated substation using probability-based algorithm,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 24, no. 1, pp. 157-166, 2017.

[8] H. H. Sinaga, B. T. Phung, T. R. Blackburn, “Partial Discharge Localization in Transformers Using UHF Detection Method,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 19, No. 6, pp. 1891-1900, 2012.

[9] Zhen Li, Lingen Luo, Gehao Sheng, Yadong Liu, and Xiuchen Jiang, “UHF partial discharge localisation method in substation based on dimension-reduced RSSI fingerprint”, IET Generation, Transmission & Distribution, Vol. 12, No.2, pp. 398-405, 2018.

[10] DITO ESD SIMULATOR data sheet. [Online]. Available: www.emtest.com/products/product/135120100000010183.pdf.