Simulation Study on GIS Partial Discharge Location Based on EMTR-DBSCAN

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2023 3rd Power System and Green Energy Conference (PSGEC) | 979-8-3503-4009-9/23/$31.00 ©2023 IEEE | DOI: 10.1109/PSGEC58411.2023.10255824

***Abstract*—Accurately detecting and locating partial discharge (PD) in gas-insulated switchgear (GIS) is critical for identifying insulation defects and improving maintenance efficiency. Recently, electromagnetic time reversal (TR) technology has emerged as an effective location method for PD. The TR process typically involves three steps: (1) recording the PD propagation signal via a sensor, (2) time reversal, and injecting the signal back into the medium, and (3) using appropriate criteria to determine the focal point corresponding to the location of the PD source. However, determining the focal time in current TR location can be challenging. To address this problem, we propose a PD location method based on TR-DBSCAN and verify its effectiveness in locating PD sources in GIS using CST simulation. We use the DBSCAN clustering algorithm to locate PD sources based on the difference between the waveforms at the signal source and non-signal source positions. This approach solves the issue of determining the focal time in three-dimensional space. The results demonstrate that our proposed method achieves precise location of PD sources in GIS with significant improvements in location accuracy.**

Keywords—GIS; partial discharge; time reversal; location; DBSCAN

I. Introduction

Gas-insulated switchgear (GIS) has been widely used in power systems due to its high level of reliability, compact size, and strong resistance to interference. However, during the manufacturing, installation, operation, and maintenance of GIS, burrs and metal particles are inevitably produced, leading to insulation defects. These defects often result in poor contact or insulation aging, causing failures that gradually escalate. Studies have shown that partial discharge occurs in insulation media before complete breakdown or flashover occurs. Therefore, it is of great significance to quickly and accurately locate the source of partial discharge to ensure the normal operation of GIS equipment.

When partial discharge occurs, various physical signals are generated, including optical signals, ultrasonic signals, and electromagnetic signals. Optical measurement equipment is complex, expensive, and has low sensitivity, and is prone to large differences in detection results due to obstruction by certain components of the equipment, making it difficult to apply in practice. Ultrasonic measurement is limited by signal transmission. The propagation of sound signals in SF6 gas is very slow, and the signal rapidly attenuates with distance, resulting in a low sensitivity of ultrasonic detection for partial discharge. The ultra-high frequency method detects the ultra-high frequency (300-3000MHz) electrical signals generated by internal partial discharge to achieve detection and location of partial discharge, with the characteristics of wide bandwidth and high sensitivity, and is suitable for large-scale spatial monitoring of partial discharge.

TR technology was initially applied in the field of acoustics. In recent years, electromagnetic time reversal technology has begun to be applied in the field of power, such as fault location in power systems, lightning location, and location of partial discharge in cables and transformers[1-4]. Compared with traditional location methods, TR only requires a single sensor and has significant advantages. However, there are still some problems with time reversal technology that have not been solved. Currently, the commonly used criteria for detecting and locating sources in time reversal are Cross-correlation and entropy[5-7]. However, the reflection and refraction of electromagnetic waves in three-dimensional space are very complex, and it is difficult to accurately determine the focal time of time reversal using the minimum entropy method.

Cross-correlation is also difficult to find the most suitable frequency.

In order to achieve enhanced accuracy and practicality in partial discharge localization within GIS, this study proposes a method based on TR-DBSCAN. The approach involves the creation of a GIS simulation model using CST Studio Suite software, where detection points are placed at the actual sensor locations to capture UHF signals originating from PD sources within the GIS simulation. Subsequently, the gathered signals are time-reversed and injected back into the GIS. However, determining the focal time during the time reversal process can pose a challenge. To overcome this challenge, DBSCAN cluster analysis is utilized to cluster the field strengths at different spatial locations, thereby enabling accurate localization of PD sources. The results show that the method has high positioning accuracy and effectively achieves the precise localization of partial discharge.

II. Principle of Time Reversal Location

It has been demonstrated that Maxwell's equations, which describe the behavior of electromagnetic fields, remain unchanged under time reversal transformations in lossless media. For PD sources in GIS, GIS can be viewed as a closed cavity. The focusing characteristics of time reversal in an empty cavity have been determined through mathematical and experimental methods. Neglecting the losses of the GIS shell and other materials, the focusing characteristics of time reversal in an empty cavity can be used to locate the PD source.

Assuming that there are multiple PD sources in the GIS that are triggered at unknown times, denoted as P points, I UHF sensors are set up to record signals. Since the time duration of a single PD is very short and can be approximated as a delta function, the excitation signal can be expressed as a sum of delta functions:

$$x_p\left[n\right] = a_p \cdot \delta\left[n - n_p\right],\ \ p = 1,2,\ldots P \tag{1}$$

where a_p and n_p are the amplitude and the instant of excitation of the p-th source, respectively. Since n_p can be different, these sources can be asynchronous, fired at different times.

The partial discharge signal is received by the UHF antenna after being propagated in the GIS cavity, and the signal $y_i\left[n\right]$ recorded by the i-th antenna is expressed as

$$y_i[n] = \sum_{p=1}^{P} a_p h_{pi}[n - n_p]\ \ i = 1,2,\ldots I\ \ n = 0,1,\ldots,N \tag{2}$$

$h_{pi}\left[n\right]$ is the transfer function of the signal from the inverse antenna *i* to the source point *p*. From the reciprocity theorem we obtain $h_{pi}\left[n\right] = h_{ip}\left[n\right]$. N is the total number of time steps in the forward simulation.

In the time inversion stage, the signal recorded at the i-th antenna is flipped in the time domain to obtain the inversion signal $y_i^r\left[n\right]$:

$$y_i^r\left[n\right] = y_i\left[N - n\right] = \sum_{p=1}^{P} a_p h_{pi}\left[N - n + n_p\right] \tag{3}$$

The signal $y_i^r\left[n\right]$ is re-transmitted by the i-th antenna and the inverse signal obtained at P is

$$\begin{aligned} s_p[n] &= \sum_{i=1}^{I} h_{pi}[n] \otimes y_i^r[n] = \sum_{i=1}^{I}\sum_{p=1}^{P} h_{pi}[m] y_i^r[n-m] \\ &= \sum_{i=1}^{I}\sum_{p'=1}^{P} a_{p'} \cdot \sum_{m=0}^{n} h_{p'i}[N - n + n_{p'} + m] \end{aligned} \tag{4}$$

$\otimes$ denotes discrete convolution. m is a new variable introduced by the convolution operation whose value is related to the signal length of the convolved signal. *p*' is the index of the source node and is intended to be distinguished from operations involving the signal source *p*.

At $n = N - n_p$, the TR signal $s_p[n]$ at the original source *p* is

$$\begin{aligned} s_p[N - n_p] &= \sum_{i=1}^{I}\sum_{p'=1}^{P} a_{p'} \sum_{m=0}^{N-n_p} h_{pi}[m] h_{p'i}[m] \\ &= \sum_{i=1,\, p=p'}^{I} a_p \left(\sum_{m=0}^{N-n_p} h_{pi}^2[m]\right) + \sum_{i=1}^{I}\sum_{p'=1,\, p'\neq p}^{P} a_{p'} \left(\sum_{m=0}^{N-n_p} h_{pi}[m] h_{p'i}[m]\right) \end{aligned} \tag{5}$$

The output signal strength $s_p[N - n_p]$ at the original source location p is much larger than the field at other non-source positions due to the presence of the autocorrelation term of $h_{pi}[n]$ and the different cross-correlation term of $h_{pi}[n]$. This produces a concentration effect of the field at the original source location *p*. During the observation of the spatial response in the time-reversal stage, the concentration effect of the field can be observed at time $n = N - n_p$, and the signal source can be reconstructed based on the maximum field strength.

By using multiple sensors to capture the electromagnetic waves emitted by a PD source, it's possible to utilize the time-reversal property of the wave equation to refocus the waves back to the source location. The effectiveness of this technique depends on the number of sensors and the loss in the propagation medium.

III. Simulation Parameters

The CST software facilitates the simulation of both the forward and time-reversal phases of the time-reversal process. CST Microwave Studio uses the finite integral technique (FIT) transient solver to simulate the propagation of electromagnetic waves in GIS, and solves Maxwell's equations in integral form.

In the GIS simulation model, in order to simulate the electromagnetic interaction between the GIS equipment and the surrounding environment, the outer cavity is set as an electric boundary. The electric boundary can reflect the perpendicularity of the electric field and the parallelism of the magnetic flux, thus simulating the propagation of electromagnetic fields between the inside and outside of the GIS.

In the forward propagation step, Gaussian pulses with frequency ranging from 0 to 3000 MHz are used to simulate partial discharge, as shown in Figure 1.The temporal form of the Gaussian current pulse is expressed as:

$$i(t) = I_0 e^{-(t-t_0)^2/2\sigma^2} \tag{6}$$

I_0 is the peak value of the pulse; σ is the decay time constant, which determines the width of the pulse; t_0 is the delay time constant.

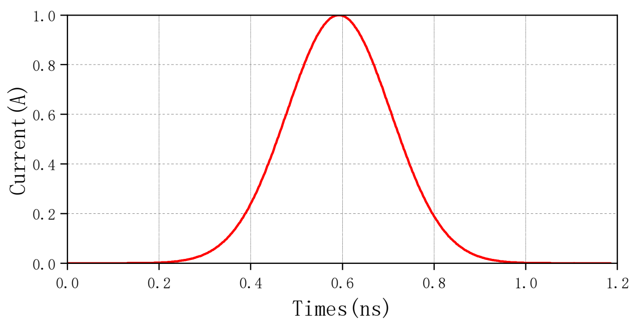
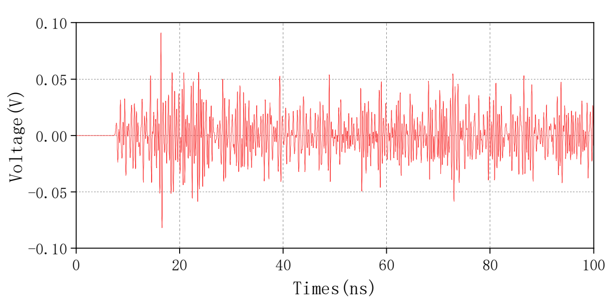
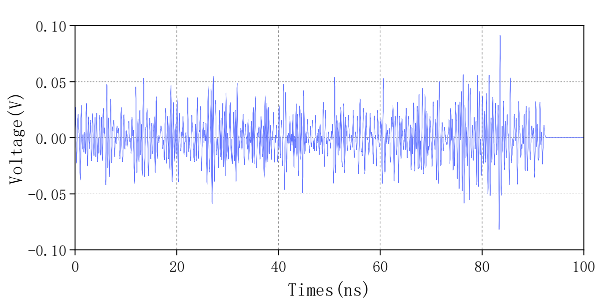


Fig. 1. Gaussian pulse

The electromagnetic waves generated in the forward stage propagate to the internal region of the GIS and are measured by simulating UHF sensors with antennas. The signals are saved and exported, processed, and then time-reversed and injected back into the CST model in the time-reversal step. An example of the signals received by the sensors and their time-reversed signals in a closed GIS is shown in Figure 2.



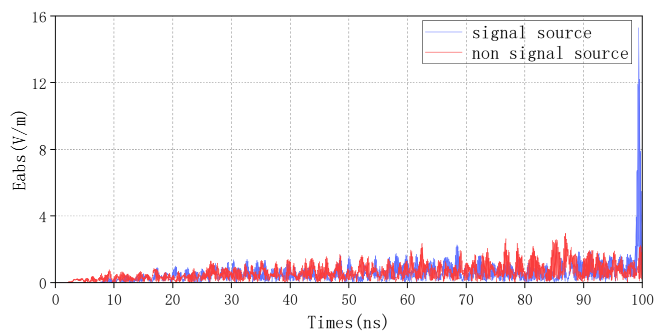
(a) Signal recorded by a sensor



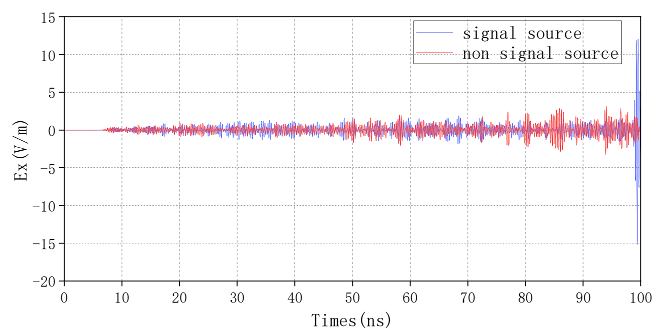
(b) Time-reversed signal

Fig. 2. signal recorded by a sensor and time-reversed signal

Figure 3 shows the x-direction (actual discharge direction) field strengths at the signal source and non-signal source locations, as well as the total field strength signals during the time-reversal process. From Figure 4, it can be observed that the received signal values at non-source points remain consistent, whereas the received signal at source points exhibits a noticeable time-focusing effect at the focal time. Moreover, the discrepancy between the received signals at different recording points during non-focal times is relatively minor. Based on these observations, it is possible to use clustering methods to pinpoint the location of the PD sources.



（a）Eabs



（b）Ex(actual PD direction)

Fig. 3. Comparison of electric field strength

Since the specific discharge direction of partial discharge is unknown in actual conditions, this paper uses the absolute value of the field strength as the basis for judgment:

$$E_{abs} = \sqrt{E_x^2 + E_y^2 + E_z^2} \tag{7}$$

IV. TR-DBSCAN Algorithm

The following process is used to locate the PD source: (1) Electromagnetic waves from one or more sources are measured at the sensor location. (2) The collected waveform is time-reversed and numerically injected into the medium. (3) During the time-reversal stage, detection and location standards for PD sources are applied to obtain the focus. In this paper, we propose a new standard for the third step, namely the DBSCAN algorithm. The algorithm flowchart is shown in Figure 4:

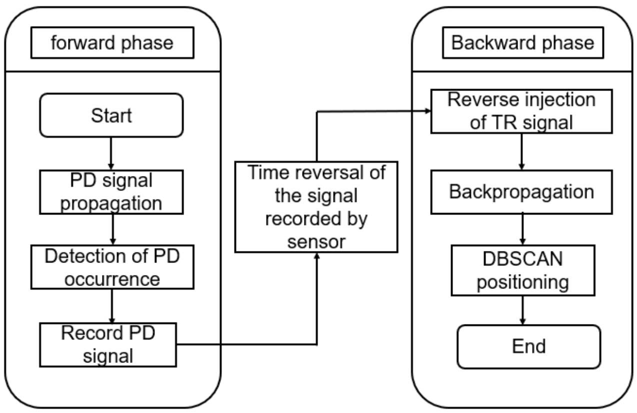


Fig. 4. TR-DBSCAN algorithm

A. *Time Reversal*

1) *Forward stage*

- Propagation: Simulate PD electromagnetic waves and simulate the spatiotemporal propagation of electromagnetic waves in the internal space of the GIS.
- Detection: UHF sensors detect the electromagnetic waves generated by PD.
- Recording: The signals received by the sensors are recorded.

2) *Time-reversal stage*

- Time reversal: The recorded signals are processed and time-reversed.
- Injection: The time-reversed signals are injected back into the medium at their corresponding detection points (i.e., sensor locations).
- Backward propagation: Simulate the backward propagation of waves in the internal space of the GIS.
- Location: Use the DBSCAN algorithm to locate the focal points of PD spatial concentration.

B. *DBSCAN*

Clustering refers to the process of grouping unlabeled data or data points into clusters based on their similarities.

In this study, the DBSCAN algorithm is utilized to identify the actual partial discharge source. Unlike other clustering approaches such as partitioning and hierarchical clustering, DBSCAN defines a cluster as the maximal set of dense connected points. This feature enables the algorithm to identify arbitrary-shaped clusters in noisy spatial databases and partition areas with sufficiently high density into clusters[8]. As a result, the DBSCAN algorithm has become a popular choice for multi-source signal clustering.

DBSCAN operates on the principle that a "central" clustering point (known as the core point) must have a minimum number of points within its radius. The points within this radius are referred to as neighborhood points, while those on the edge of the neighborhood are boundary points. Points that exceed the radius belonging to a certain cluster and do not meet the minimum number of points to become a core point are classified as noise points.

In order to carry out the clustering process, the DBSCAN algorithm necessitates the manual setting of two parameters, namely the neighborhood radius (ε) and the minimum number of points (MinPts) within the neighborhood. Specifically, the ε-neighborhood is constituted by the set of sample points x_i in the dataset D that are located at a distance of ε or less from the sample point:

$$N_{\varepsilon}(x_i) = \{x_j \in D \mid dist(x_i, x_j) \le \varepsilon\} \tag{8}$$

The density of a sample point can be estimated by the number of points x_i in its ε-neighborhood. MinPts refers to the minimum number of sample points x_i required to be present in the ε-neighborhood of a given sample point to consider it a core point.

V. Results and Analysis

A. *single-phase GIS*

To verify the feasibility and effectiveness of time-reversal, the location effect of single-phase GIS is first studied. The model consists of components such as conductors, disc insulators, metal shells, and flanges, and contains three SF_6 chambers separated by disc insulators, as shown in Figure 5. The diameter of the inner conductor is 80mm, the outer shell diameter is 500mm, the insulator thickness and outer diameter are 70mm and 560mm, respectively, and the flange thickness is 25mm. The disc insulator material is made of epoxy resin with a dielectric constant of 3.8.

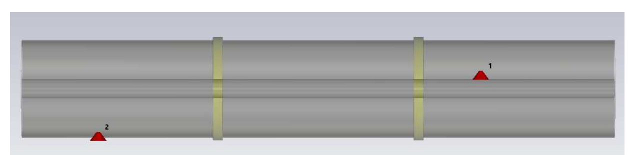


Fig. 5. Single-phase GIS

Taking the center point of the leftmost cross-section of the simulation model as the origin, establish a coordinate system as shown in the figure 6 (unit in millimeters, z-axis along the axis direction). The PD is located near the GIS conductor, with a length of 10mm and a central coordinate of (65, 0, 2400). The UHF sensor is placed directly below the shell, with a position coordinate of (225, 0, 400).

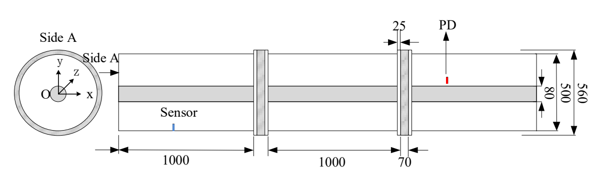


Fig. 6. Distribution of PD and probe in the simulation model

In the GIS, the Gaussian pulse generated by partial discharge will propagate in space. The voltage waveform is recorded at the sensor location, time-reversed and deconvolved, and the processed signal is injected into the internal space of the GIS at the sensor location. During this process, the field strengths at various locations in space are recorded with a 0.05ns time interval within 100ns. Due to limitations in data density, field strength sampling is performed according to 30×30×10mm.

The data obtained by processing with the DBSCAN clustering algorithm is used to locate the PD source. The data points are classified into different categories to determine the location of the PD source. After determining the center position of the cluster, the sampling point closest to the cluster center can be found and used as the signal source position to determine the location of the PD source, as shown in Figure 7:

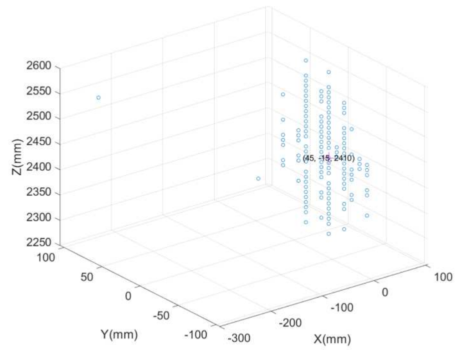


Fig. 7. PD positioning in single-phase GIS

We can see that TR-DBSCAN achieves effective location of PD in single-phase GIS.

B. Noise

Conventional UHF location techniques are highly sensitive to noise and in noisy environments their recording start times can be affected, thus reducing the accuracy of location. To address this problem, the effects of noise are investigated..

The signal captured by the sensor during the forward phase may be subject to noise, thereby causing a signal-to-noise ratio (SNR) of 10dB. Figure 8 shows an example of the resulting signal that has been corrupted by noise. During the reverse phase, a noisy time-reversal signal is introduced into the medium, with the same methodology being repeated utilizing a 5dB SNR signal.

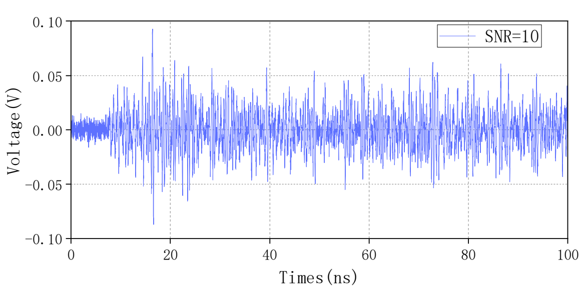
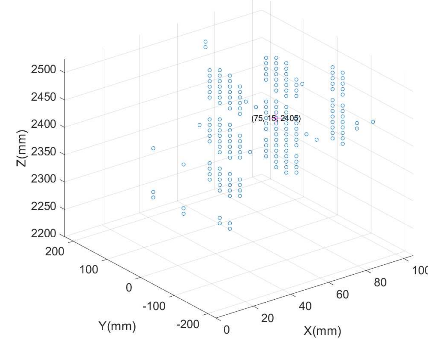
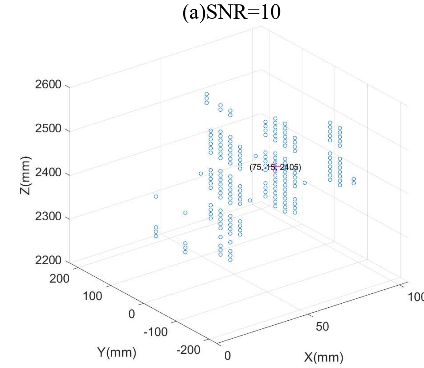


Fig. 8. Noise-added signal

Figure 9 depicts the outcomes derived from the EMTR approach at 5dB and 10dB. The results reveal that the EMTR technique is quite effective, as it can accurately detect the location of the PD with a reasonable level of precision (39 mm at both 5 dB and 10 dB SNR levels).



(a)SNR=10



(b)SNR=5

Fig. 9. PD location under noise interference

C. Multiple PD sources

In an actual operating GIS, partial discharges may occur in multiple locations, which may result in the accuracy of the EMTR technique being compromised. The signal injected into the medium becomes more complex because the signals generated by multiple PD sources can interfere with each other. EMTR techniques need to process multiple complex signals, which can make it more difficult to locate the location and number of PD sources.

In this case, the situation that there are three partial discharge sources PD1, PD2 and PD3 at the same time is considered, and the positioning result is shown in Figure 10. The specific data is in Table I:

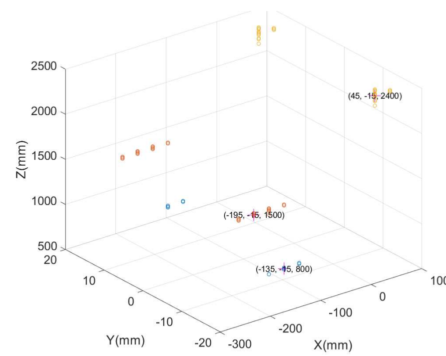


Fig. 10. PD location with multiple sources

TABLE I. MULTI-PD SOURCE POSITIONING RESULTS

PD	Actual position /mm	Location result/mm	Distance/mm
1	(65,0,2400)	(45, -15, 2400)	25
2	(-175,0,1500)	(-195, -15, 1510)	26.93
3	(-125,0,800)	(-135, -15, 800)	18.03

As can be seen in Table I, there is still excellent location for multiple sources.

D. Complex structure

In addition to the long straight tube structure, the GIS also includes several bent structures, with L-shaped bends and T-shaped branches being the most common corner structures. The passage of UHF electromagnetic waves generated by partial discharges through L-shaped and T-shaped structures will influence their propagation characteristics. Consequently, it is crucial to investigate the time-reversal characteristics of partial discharges under more intricate structures.

A GIS model containing three L branches is established, as shown in Figure 11. A PD source is set at the position of port 1, and a circular UHF sensor for time-reversal location, as shown in Figure 12, is used at port 2.

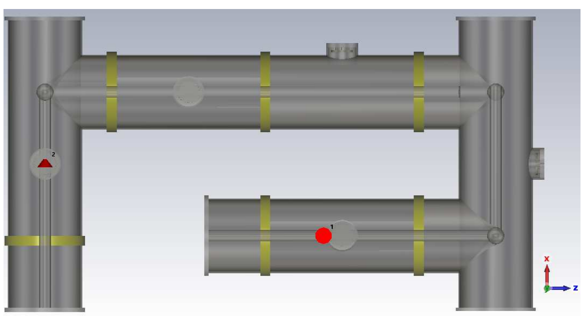
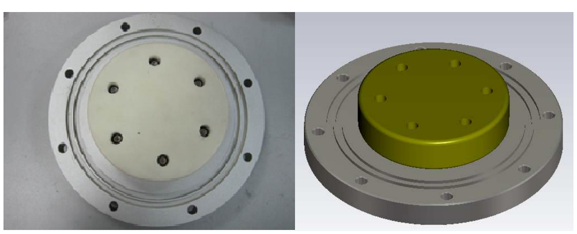


Fig. 11. Complex GIS model



(a) (b)

Fig. 12. Disc UHF sensor

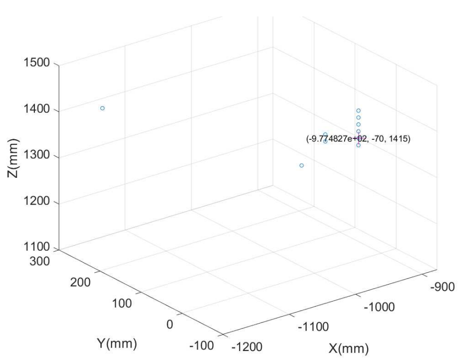


Fig. 13. PD location in complex GIS structure

The initial position of the signal source is (-1000, -65, 1440), and the location point of the signal source after time inversion is (-977.5, -70, 1415), as shown in Figure 13, the error distance is about 34mm. The initial position of the signal source is at (-1000, -65, 1440), and the located position of the signal source after time-reversal is at (-977.5, -70, 1415), with an error distance of about 34mm. Even under complex structures, EMTR can still achieve good location effect for partial discharges.

VI. CONCLUSION

The TR-DBSCAN technology proposed in this paper for locating PD has been extended from simple structures to more complex structures in GIS, and the following conclusions have been drawn:

1) This technology can effectively locate PD in GIS using only one sensor, which has a huge advantage.

2) Considering different practical situations such as noise, complex structures, and multiple PD sources, it demonstrates that EMTR technology has good application prospects for complex interference environments in the field.

3) The DC-DBSCAN algorithm can effectively achieve precise localization of the PD source, solving the problem of difficult judgment of the signal source in three-dimensional space using minimum entropy.

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