

Automatic Localization of Partial Discharges in GIS Based on Digital Twins

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Abstract: The current predominant method for partial discharge (PD) localization necessitates manual measurements of the distances between sensors and time-of-arrival differences by maintenance personnel. To enhance the intelligence of automatic localization techniques, this paper conducted research on PD localization within Gas-Insulated Switchgear (GIS) using digital twin technology. We propose an automatic PD localization technique for GIS based on digital twins. Initially, we establish a digital twin model of a typical GIS, compute the shortest distances between any two points within the model, thus creating a "time delay fingerprint database." Using this database in conjunction with the time-of-arrival difference method allows for the automatic localization of partial discharges. The effectiveness of this algorithm has been verified through simulation experiments.

Keywords: Digital Twin; Arrival time difference; Automatic positioning; Partial discharge

1. Introduction

Gas Insulated Switchgear (GIS), as a critical component in modern power systems, has gained widespread use due to its compact size, high integration, and excellent insulation performance [1]. However, during operation, GIS equipment is susceptible to experiencing Partial Discharge (PD) phenomena. PD is a minor electrical discharge caused by insulation defects, solid impurities, insulation surface contamination, and free conductive particles [2-5]. If these discharges are not promptly controlled and addressed, they can generate powerful electromagnetic fields and heat within the equipment, further deteriorating its insulation performance and potentially leading to severe damage or even power system failures and outages [6-8].

However, existing techniques still exhibit certain limitations, such as insufficient localization accuracy, sensitivity to environmental disturbances, poor real-time performance, and an inability to meet the high-precision and real-time requirements of PD detection [8]. Therefore, enhancing the accuracy and real-time capabilities of PD detection and localization is a pressing challenge for current researchers [9,10].

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In recent years, Digital Twin technology, as a novel digital approach, has found widespread applications across various domains [11]. Digital Twin technology enables real-time monitoring of equipment, timely detection of abnormal behaviors, proactive prevention of equipment failures, and significant improvements in operational efficiency and safety [12-15]. Therefore, exploring the application of Digital Twin technology in the automatic localization of PD within GIS has the potential to address existing technological challenges and enhance the precision and real-time capabilities of PD localization, making it a valuable area of research [16].

Consequently, in response to the limitations of current automatic localization techniques for PD in GIS online monitoring systems, and leveraging the advantages of Digital Twin technology, this paper undertakes research in PD localization within GIS based on Digital Twins. We propose an automatic PD localization technique for GIS based on Digital Twins. Initially, we establish a Digital Twin model of GIS, calculating the shortest distances between any two points within the model to create a fingerprint database. Subsequently, automated PD signal localization is achieved using time-of-arrival difference methods. The effectiveness of this algorithm is validated through simulation experiments.

2. Analysis of Partial Discharge Source Localization

2.1. Time-of-Arrival Difference Localization Method

Due to its simple technical principles, the Ultra-High-Frequency Time-Difference (UHF To AD) localization method (Figure 1) has been widely applied in the localization of partial discharges in transmission and substation equipment. It determines the distance between the discharge source and sensors based on the time difference between the arrival of discharge pulses at two sensors, employing a bidirectional ranging technique.

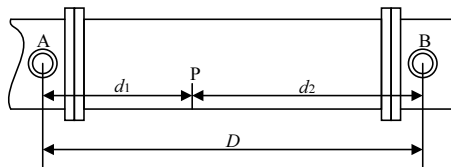


Figure 1. Time Difference Positioning Method.

P represents the location of a partial discharge defect, while A and B denote the positions of sensors 1 and 2, respectively, situated on either side of the partial discharge defect. The distance along the GIS pipeline between them is denoted as D . Assuming a discharge pulse arrives at points A and B from point P at times t_1 and t_2 , respectively, and the propagation speed of the discharge pulse within the GIS is the speed of light, c , then the distances d_1 and d_2 from point P to points A and B can be respectively expressed as Eq. (1):

$$d_1 = ct_1, d_2 = ct_2 \tag{1}$$

The distance from point P to sensor A can be calculated using the Eq. (1):

$$\begin{aligned}
d_1 &= ct_1 = D - ct_2 \\
&= \frac{D - ct_2 + ct_1}{2} \\
&= \frac{D - c(t_2 - t_1)}{2}
\end{aligned} \tag{2}$$

From Eq. (2), it is evident that by calculating the time difference between t_1 and t_2 , you can obtain d_1 . The time difference between t_1 and t_2 can be represented as follows:

$$\Delta t = t_2 - t_1 \tag{3}$$

Therefore, Eq. (2) can be rewritten as follows:

$$d_1 = \frac{D - c\Delta t}{2} \tag{4}$$

The position of the two sensors and the propagation speed of the discharge pulse are predetermined. Therefore, the key to determining the accuracy of the localization result lies in the precision of time difference calculation. As the propagation speed of the discharge pulse is the speed of light and the distances involved are within a few meters, the time difference should be in the nanosecond range. Hence, this method demands extremely high precision in time difference measurement.

Traditional GIS time-of-arrival difference localization requires the use of high-speed oscilloscopes with a sampling rate of no less than 10 GS/s. In the field, manual triggering of partial discharge signals is necessary, followed by manual calculation of the time difference of pulse arrival and the localization result.

2.2. Digital Twin Technology

Digital twin technology is an advanced digitalization technique that has gained significant traction in recent years and holds immense promise in the field of power systems [17]. Given the complexity of power equipment and the stringent requirements for stable operation, real-time monitoring and predictive maintenance of equipment are of paramount importance [18].

Furthermore, digital twin technology offers substantial advantages in the context of PD localization within GIS. Firstly, by constructing precise models of GIS equipment, we can simulate PD events accurately, enhancing the accuracy of localization. Secondly, utilizing real-time data, we can achieve real-time PD localization, enabling early warning and proactive management of PD issues, thus reducing their impact on the power system [19]. Additionally, the application of digital twin technology allows for the visualization of the localization process, making the results more intuitively accessible and user-friendly [20].

In summary, digital twin technology provides a fresh perspective and powerful tools for addressing the challenge of PD localization in GIS. In the following sections, we will delve into how digital twin technology can be applied for the automatic localization of PD within GIS.

3. Automatic Localization of Partial Discharges in GIS Based on Digital Twins

To address the shortcomings of the current automatic localization techniques in GIS-based partial discharge online monitoring systems, this study integrates the advantages of digital twin technology. The research undertakes a PD localization investigation in GIS based on digital twins and proposes a novel automatic PD localization technique. The key steps involve:

Establishment of a Comprehensive GIS Digital Twin Model: Initially, a holistic digital twin model of the GIS system is constructed. This model meticulously represents the physical structure, material properties, and electrical characteristics of the GIS equipment.

Calculation of Shortest Distances: Within the digital twin model, the computation of the shortest distances between any two points is carried out. This information is harnessed to generate a database of delay fingerprints.

Time-of-Arrival Difference Localization: Employing the time-of-arrival difference method, the automatic localization of partial discharge signals is seamlessly executed.

3.1. Modeling of Digital Twin for GIS

The present study utilizes Solidworks software as the primary tool for constructing the digital twin model. The established digital twin model can be broadly categorized into two main types: the Display Model and the Computational Model.

The Display Model, as depicted in Figure 2, provides an intuitive representation of various characteristics of GIS equipment. This model offers convenience to on-site testing personnel during maintenance operations.

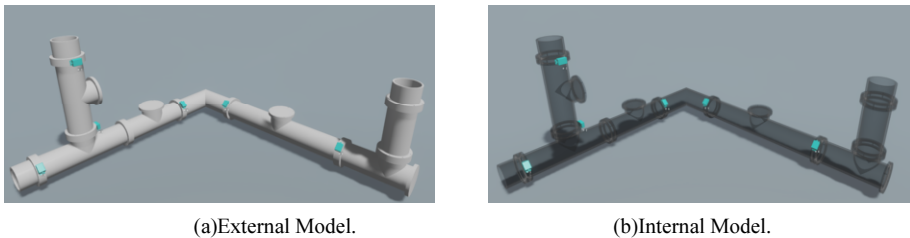


Figure 2. Display Model.

The Computational Model, as illustrated in Figure 3, is primarily employed for simulating and predicting the operational states of GIS equipment under different conditions. Its objective is to achieve a more precise identification and localization of partial discharges.

Furthermore, this subdivision approach also aids in gaining a better understanding of the operational conditions of GIS equipment and the impact of partial discharges. By observing the Display Model, we can intuitively comprehend the equipment's structure and operational status. Meanwhile, through the Computational Model, we can delve deeper into understanding the effects of partial discharges and how to more effectively localize and address them. In the future, we plan to further optimize and expand both models to comprehensively and thoroughly explore the impact of partial discharges and their mitigation strategies.

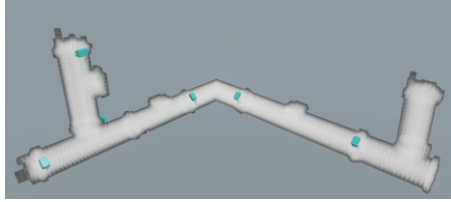


Figure 3. Computational Model.

3.2. The Shortest Transmission Path for Ultra-High-Frequency Signals

In the GIS digital twin model, for the convenience of calculating the time difference between the partial discharge source and various UHF sensors, it is essential to enable the model to automatically compute the shortest paths for UHF signals between any two points. To achieve this goal, this study has selected the Dijkstra algorithm as the primary pathfinding algorithm.

The Dijkstra algorithm is a classical method for solving the single-source shortest path problem and has been widely applied in various fields, including network routing and GIS. This algorithm is capable of finding the shortest paths from the source node to all other nodes and calculating the lengths of these paths. Here is a detailed explanation of how the Dijkstra algorithm works:

Initialization: Start by designating the source node as the "current node" and set the distance from the source node to itself as 0. For all other nodes, set their distances to the source node as infinity (or a sufficiently large value).

Begin the iteration process: In each iteration, perform the following steps:

Choose the neighbor node of the "current node" with the shortest distance to the source node and set it as the new "current node."

Update the distances of all neighbor nodes of the "current node." Specifically, for each neighbor node, calculate the length of the path from the "current node" to that neighbor. If this path length is shorter than the previously known shortest path, update the distance value of the neighbor node.

During each iteration, the algorithm updates and maintains the shortest distances from all nodes to the source node. This greedy strategy ensures that the algorithm consistently finds the shortest paths.

Mark the "current node" as "visited" when all nodes have been traversed.

The algorithm terminates under the following conditions: either the target node is marked as "visited," or all remaining unvisited nodes have distances to the source node that are infinity.

Finally, starting from the target node, trace back through each node's shortest path until reaching the source node. This process reveals the shortest path from the source node to the target node.

After computing the distances between all pairs of points within the GIS digital twin model, a 'fingerprint database' is formed for subsequent use.

As shown in Figure 4, upon selecting any arbitrary point within the GIS digital twin model, the shortest paths from that point to each of the UHF sensors are automatically displayed within the digital twin model. These paths represent the signal propagation routes.

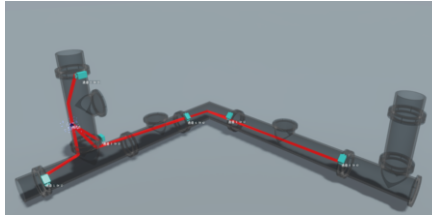


Figure 4. Shortest Dissemination Path.

3.3. Automatic Localization of Partial Discharges in GIS

While the current mainstream methods for PD localization are based on the principle of time-of-arrival difference, they still require manual selection of two sensors for calculation and the measurement of the sensor-to-sensor spacing in the field. Once the localization distance is obtained, on-site operations are necessary to determine the precise location of the discharge source. However, the GIS digital twin model can automatically compute the shortest paths and distances between any two points within the GIS pipeline, making it possible to automatically calculate the time difference of UHF electromagnetic wave pulses arriving at any two sensors when a PD event occurs. This eliminates all manual measurement tasks and allows for the intuitive display of PD localization results within the GIS digital twin model.

The specific steps are as follows (Figure 5):

Step 1: In the GIS digital twin model, there are M internal coordinates within the GIS, and S locations suitable for deploying UHF sensors (non-shielded insulation bushings). Traverse the M internal coordinates within the GIS and calculate the signal transmission distances from each point to the deployment locations of S sensors, creating a transmission distance fingerprint database.

Step 2: Conduct on-site UHF PD detection. After setting the positions of each detection sensor on the model, data collection begins. Assuming that two sensors, A and B, detect PD data, the expected time difference Δt for the PD pulse to arrive at these two sensors can be calculated.

Step 3: Convert the expected time difference into an expected distance difference, $\Delta d = c \times \Delta t$, where c is the speed of light.

Step 4: Utilize the transmission distance fingerprint database to search for all coordinate points X that satisfy $DA - DB = \Delta d$, i.e., all coordinate points for which the difference in distance to sensors A and B is Δd . Highlight these coordinate points as localization results within the GIS digital twin model.

4. Simulation Experiment Analysis

4.1. Construction of GIS Simulation Model

For empirical research, this paper has established a simulated experimental platform based on GIS, as depicted in Figure 6. This experimental platform injects electromagnetic wave signals to simulate partial discharge, which is a realistic approach for simulating partial discharge scenarios and validating external PD signal recognition algorithms.

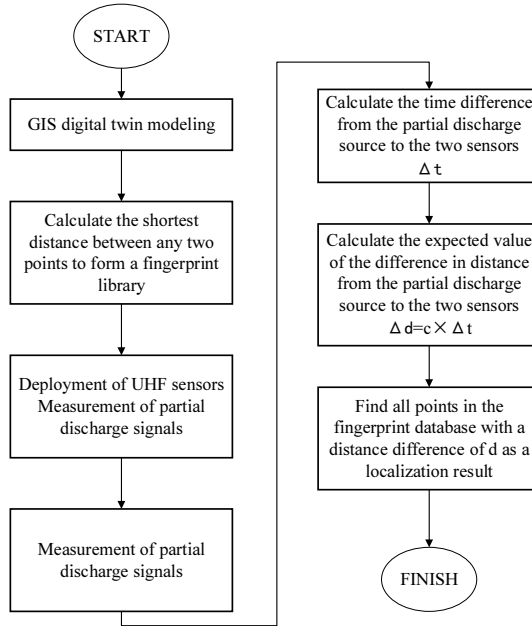


Figure 5. Automatic Positioning Process.



Figure 6. GIS PD experimental platform.

Specifically, the outer diameter of the GIS simulated pipeline's casing is approximately 560 millimeters, while the inner coaxial conductor has a diameter of approximately 160 millimeters. The model's sampling frequency is set between 300 MHz and 1.5 GHz, which is sufficient to meet the requirements for simulating partial discharge signals.

Furthermore, this study employs the YWDT-12/120kV power frequency non-partial discharge test transformer as an external power source to apply voltage to simulate GIS conditions. By gradually increasing the pressure within the chamber, various degrees of partial discharge scenarios can be simulated, thus further enhancing the experimental conditions.

"Using the modeling approach presented in this paper, the simulated GIS pipeline was accurately modeled. Test personnel installed six external UHF sensors at non-shielded flange locations, guided by intelligent positioning."

4.2. Experimental Results

Test personnel injected electromagnetic wave signals at the T-shaped corner using a spark plug, simulating the situation of internal partial discharge in the GIS pipeline. The GIS simulated pipeline was equipped with six UHF sensors. Real-time PRPD spectrograms were monitored at the installation locations of each UHF sensor. The blue lightning marker indicates the location of the PD source. As shown in Figure 7, the results demonstrate that the localization of the partial discharge indeed occurred at the T-shaped corner, with a localization error of less than 0.5 meters, aligning with the experimental expectations.

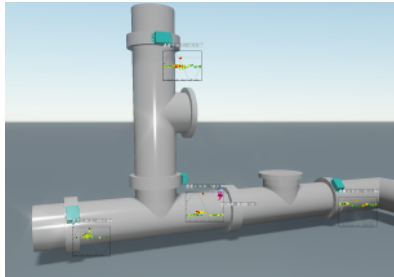


Figure 7. Experimental results graph.

5. Conclusion

This paper undertook an investigation into the automatic localization of partial discharges in GIS through the utilization of digital twin technology. The paper introduced a technique based on digital twins to automatically pinpoint the source of partial discharges within GIS. A digital twin model of the GIS was developed for this purpose.

The research involved the computation of the shortest propagation paths between any pair of points within the GIS, resulting in the creation of a comprehensive fingerprint database. The automatic localization of partial discharge signals was accomplished through the utilization of the time-of-arrival difference method.

To verify the effectiveness of the proposed method for automatic localization of partial discharges within GIS, a simulation experimental platform for GIS was established. This platform was employed to conduct simulation experiments, validating the proposed method's functionality and precision.

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