New Energy and Future Energy Systems
G.L. Kyriakopoulos (Ed.)

doi:10.3233/ATDE231074

A GIS Digital Twin Modeling Approach Applied to Partial Discharge Live Test

Yizhi FANG[a, 1], Yuling LIN[a], Zicong QIU[a], Minhua HUANG[a], Tianshu LI[a], Daoyi SHEN[b] and Dan ZENG[c]
[a] *Zhuhai Power Supply Bureau, Guangdong Power Grid Corporation, Zhuhai, Guangdong Province, China 519000*
[b] *Global Science & Technology (Shanghai) Co., Ltd, Shanghai, China, 201210*
[c] *Shanghai University, Shanghai, China, 200444*

Abstract. Gas Insulated Switchgear (GIS) ultra high frequency (UHF) live test presently stands as the most widely employed technique for partial discharge detection in the field. With the ongoing digital transformation of the power grid, the imperative has arisen to advance partial discharge detection toward intelligence and automation. Accordingly, this paper puts forth a digital twin modeling approach for GIS live test, through a comprehensive examination of digital twin technology. This approach encompasses the establishment of a GIS digital twin model, the assessment of both internal and external UHF signals of the GIS, as well as the intelligent guidance for the deployment of UHF sensors, among other aspects. The findings of this study hold significant implications for the maintenance and servicing of GIS equipment.

Keywords. Digital twin, partial discharge, GIS, live test

1. Introduction

Gas-insulated switchgear (GIS) constitutes a pivotal power equipment category extensively deployed in high-voltage transmission and substations [1]. The occurrence of partial discharge defects inside GIS due to improper installation, switching operations, and external environmental factors presents a substantial risk, potentially leading to insulation breakdown and prolonged equipment malfunction in high-voltage systems. Consequently, there is an imperative to engage in research and development efforts aimed at establishing effective partial discharge detection technologies [2-3].

The UHF live test technology serves as a highly effective approach for detecting partial discharges in GIS equipment [4]. It involves the manual placement of sensor detectors within the GIS insulation basin or observation window, enabling real-time detection and diagnosis of partial discharge signals emanating from GIS equipment [5]. This methodology facilitates the identification of defects and the formulation of appropriate corrective measures [6]. Consequently, it enhances equipment reliability and safety, reduces maintenance and replacement costs, and contributes to the overall quality and reliability of power supply in the grid [7-10].

[1] Corresponding Author: Yizhi Fang, zhfyz@126.com.

In recent years, digital twin technology, emerging as a virtual simulation paradigm, has found widespread application across various domains [11]. Its fundamental premise revolves around the establishment of digital models representing physical entities, thereby facilitating functions such as virtual simulation, data analysis, and decision support. Digital twin technology has demonstrated diverse and practical applications within the field of partial discharge condition monitoring [12]. The realization of power grid digitalization and the transition towards intelligent operation and inspection critically depend on the support and integration of digital twin technology [13-16].

Hence, recognizing the excessive reliance on manual expertise in the current context of GIS partial discharge live test, this study leverages the inherent advantages of digital twin technology. It endeavors to explore intelligent approaches to GIS live test based on digital twins. The paper introduces a GIS digital twin modeling methodology specifically tailored for partial discharge live test. This methodology encompasses the creation of a GIS digital twin model, enabled by software-driven processes.

Employing the assistance of sophisticated software, this model guides the placement of test sensors during each stage of the live test in a three-dimensional visual wizard mode. The software dynamically adjusts sensor positioning to align with the prevailing real-world conditions, ensuring optimal deployment. Furthermore, it intuitively displays the results of sensor positioning on the model upon detecting partial discharges. This transformative approach significantly elevates both the efficiency and reliability of the testing process, addressing the challenges associated with manual methods and enhancing the overall quality of live test in GIS equipment.

2. GIS Partial Discharge Live Test

In the current traditional GIS partial discharge live test process, the portable multi-channel partial discharge detector is usually carried by the operation and maintenance personnel and the sensors are deployed on the surface of the GIS for detection. As shown in Figure 1, the detector usually contains 6 UHF sensors, which are fixed in 6 detection positions on the GIS. The instrument synchronously collects the partial discharge signals from the 6 channels, and diagnoses and locates the signals through the PC software.

Fig. 1. Portable multi-channel partial discharge detector.

In line with this approach, the initial detection point is typically chosen to feature six unshielded insulators, as exemplified in Figure 2. Each of these sensors is meticulously positioned to ensure comprehensive coverage and effective signal acquisition within the designated GIS area.

Fig. 2. UHF sensor installation location.

Subsequently, the partial discharge detector is employed to capture the partial discharge signals emanating from each of the six sensors. This collection process yields critical data, including signal attributes such as amplitude, frequency, and other relevant information. Based on this dataset, PRPS (Partial Resonance Spectroscopy) and PRPD (Partial Discharge Pattern) maps are meticulously generated. These maps serve as essential tools for the identification and classification of different types of partial discharges encountered during the inspection and monitoring proess.

If none of the sensors detects a localized discharge signal, the inspection for the current interval concludes, and the process proceeds to the next interval for testing. However, if any of the sensors registers a localized discharge signal, it necessitates the consideration of potential external interference.

During this phase, the inspector must determine whether the detected signal originates from within the GIS or if it is a result of external factors. This determination is typically achieved by comparing signal amplitudes between the sensors. Alternatively, an additional external noise sensor may be deployed to facilitate this comparison by evaluating signal amplitudes in conjunction with the GIS sensors. Should it be ascertained that the signal emanates from within the GIS, the next step involves localizing the internal discharge source.

In the localization process, the inspector selects pairs of sensors for localization, employing the arrival time difference method. During localization, it is imperative to measure the distance along the GIS pipeline between the two selected sensors. Each localization attempt yields a distance along the GIS propagation path of the discharge source from one of the sensors. This process is repeated sequentially with different sensor combinations. The final localization result is derived when the localization result falls within the spatial range between the two selected sensors, and the distance from both sensors exceeds the localization error margin.

Subsequently, the inspector estimates the size of the localized discharge source based on the localization result. By integrating the type and location of the discharge, an evaluation of the potential hazards associated with the localized discharge is conducted. Relevant countermeasures are then designated to mitigate identified risks effectively.

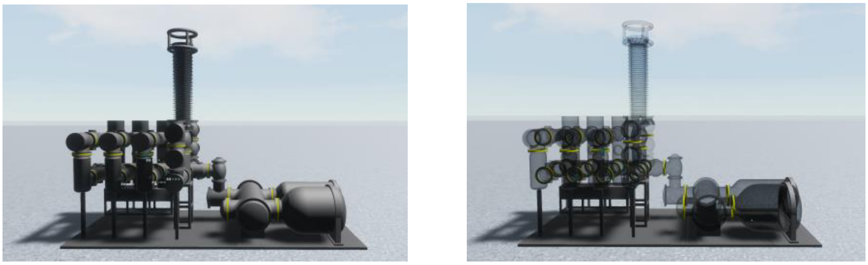
3. Key Techniques for Modeling GIS Digital Twin Models

In response to the challenges outlined above, this paper introduces a GIS digital twin modeling method tailored for partial discharge live test.

3.1. GIS Digital Twin Modeling

3.1.1. GIS Digital Twin Model Modeling Approach

In this paper, Solidworks software has been selected as the modeling tool to construct a three-dimensional representation of the Gas Insulated Switchgear (GIS) [17]. This model is based on GIS drawings and precise measurements taken on-site. It's worth noting that the digital twin model proposed in this study is specifically designed for the application of partial discharge live test. Therefore, the modeling focuses exclusively on the external surface of the GIS pipe (pipe wall), which is modeled with a thickness of 0.001 meters. The interior of the pipe is left empty, and the internal structure of the GIS is not included in the model.



(a)external model (b)internal model

Fig. 3. Display model.

The digital twin model created in this research is divided into two main components: a display model and a calculation model. The display model, as depicted in Figure 3, serves the purpose of presenting the characteristics of the GIS equipment in a visually intuitive manner. This presentation aids in guiding testers effectively through their operation and maintenance tasks, providing them with a clear and accessible reference point for their work.

In the process of utilizing Solidworks software to model the external surface of the GIS pipe, various internal components of the GIS, including the internal bus, circuit breaker, disconnect switches, current transformers, voltage transformers, shielded insulated pots, non-shielded insulated pots, and other parts along the pipe wall, are distinguished by assigning different materials and names. For instance, the material assigned to the bus is designated as "bus," the circuit breaker material is labeled "circuit breaker," and so forth. To illustrate further, the material for the busbar is identified as "Busbar," while the circuit breaker material is specified as "Circuit Breaker."

Additionally, all insulated basins where sensors can potentially be deployed are uniformly designated as "unshielded basin." With the completion of the model, for any given point located within the GIS, the material name associated with the closest wall to that point serves as an indicator of the type of GIS component situated at that specific location. This material-naming scheme facilitates the precise identification and classification of GIS components within the digital twin model, enhancing its utility for guided testing and maintenance activities.

3.1.2. GIS Internal and External Judgment

Upon the completion of the GIS digital twin modeling process, it becomes imperative to automatically ascertain whether a specific point resides within or outside the GIS device.

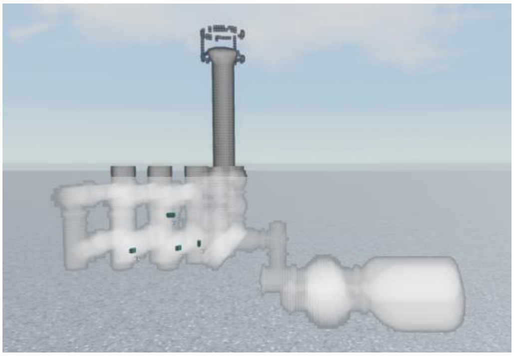


Fig. 4. Computational models.

For a GIS device, as depicted in Figure 4, the dimensions of the scene are considered to be (50 meters, 20 meters, 10 meters), representing its maximum extents along the X, Y, and Z directions as 50 meters, 20 meters, and 10 meters, respectively. The entire scene is divided uniformly into square cells, each with side lengths of 0.1 meters, facilitating the expression of any point's position within the scene as numerical coordinates.

To determine whether a point within the scene is located inside the GIS, the following methodology is employed:

Rays Projection: For any digital coordinate point within the scene, a total of 14 rays are emitted from the center of the small square in which the point is situated. These rays project outward along the central axes of the six faces and eight vertices of the small square. Each ray extends in both the direction of the face centers and the vertices of the square.

Collision Detection: The behavior of these rays is assessed concerning their interaction with the GIS model. Specifically, it is determined whether each of the 14 rays intersects with the GIS model before reaching the boundary of the scene. If any of these rays fails to collide with the GIS model, signifying that it does not intersect with the coordinates occupied by the GIS model, the respective coordinate point is concluded to be situated outside the GIS. Conversely, if all 14 rays successfully intersect with the GIS 3D model before reaching the scene boundary, confirming their intersection with the coordinates occupied by the GIS model, the coordinate point is confidently categorized as being located within the GIS.

By implementing this method, the system effectively discerns whether any given point resides within the interior of the GIS digital twin. This determination provides crucial and precise spatial localization information for subsequent computations and analyses within the digital twin model.

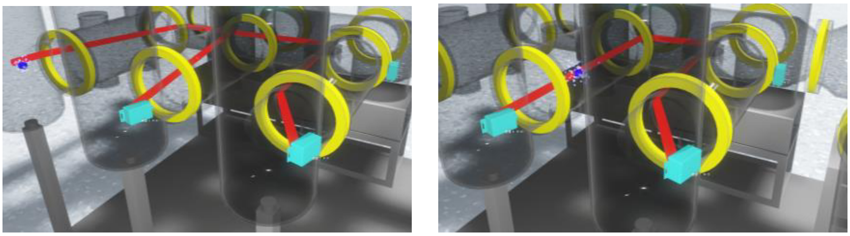
3.2. UHF Sensors Deploy Intelligent Guidance

3.2.1. Principles of UHF Sensor Deployment

Following the achievement of automatic localization of partial discharge sources, the system plays a pivotal role in guiding operational and maintenance personnel to deploy additional UHF sensors, thereby facilitating precise localization. To illustrate this process, let's consider a GIS digital twin model and delve into the deployment principles of UHF sensors.

First, let's analyze the first case: When the localized discharge source falls outside the region enclosed by two sensors, the difference in its distance to the two sensors remains a constant value, equivalent to the separation distance between the two sensors, as depicted in Figure 5(a).

Next, let's examine the second case: In scenarios where a T-shaped branch exists between the two sensors, the disparity in the distance from any position along the branch to the two sensors consistently equals the difference in distance from the T-shaped branch to the two sensors, as exemplified in Figure 5(b).



(a) Test points are located outside the two sensors. (b)The test point is located between the two sensors.

Fig. 5. Location of partial discharge source occurrence.

In both cases, the system aids in ensuring the effective placement of additional UHF sensors to enhance localization accuracy and provide comprehensive coverage of potential discharge sources. This approach streamlines the deployment process and optimizes the detection capabilities of the GIS digital twin model.

Taking into consideration the localization error, we can establish the following principles:

When the distance between the localization result and any one sensor is less than or equal to the localization error, it suggests that the partial discharge power source could be situated either at the localization result or outside the region encompassed by the two sensors.

When the distance between the localization result and the T-branch junction between two sensors is less than or equal to the localization error, it indicates that the partial discharge power source could potentially be located at any point within the T-branch channel.

Given these principles, and in order to fulfill the requirements of UHF partial discharge localization within GIS, we propose the following sensor deployment principle: Sensors should be strategically positioned along all conceivable paths through which partial discharge signals may propagate. These sensors should collectively encircle the suspected partial discharge power source, ensuring that the distances between the sensors and the potential discharge source exceed the localization error. This approach guarantees comprehensive coverage and localization accuracy for the detection of partial discharges in GIS.

3.2.2. Intelligent guidance for UHF Sensors

Building upon the previously established UHF sensor deployment principles, let's continue to consider a GIS digital twin model as an example, as depicted in Figure 6. In this scenario, achieving full coverage of the interval can be accomplished by installing six UHF sensors strategically positioned to cover the entire span.

Operational and maintenance personnel are guided to install these UHF sensors in predetermined and fixed positions, as illustrated in the figure. This approach serves several essential purposes:

Comprehensive Coverage: Fixed sensor placements ensure that critical measurement points are consistently covered, eliminating the risk of missing key measurement locations that could result in overlooked partial discharges.

Historical Data Accumulation: By maintaining a consistent sensor configuration, historical data can be systematically accumulated. This historical data becomes invaluable for conducting vertical comparisons over time, providing essential support for subsequent pattern recognition and automatic localization.

By adhering to these principles and guidelines, the deployment of UHF sensors within the GIS digital twin model ensures full coverage of the interval, minimizes the likelihood of missed measurements, and facilitates effective data analysis for the recognition and localization of partial discharges.

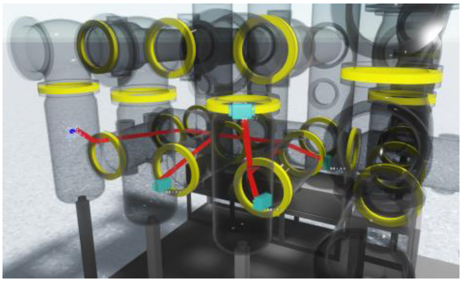


Fig. 6. UHF sensors deploy intelligent guidance.

4. Simulation Experiment Analysis

In this chapter, we establish a GIS simulation experiment platform to empirically assess the effectiveness of the modeling method proposed in this study. Through a series of simulation experiments conducted on this platform, we aim to validate the utility and reliability of the modeling approach in practical applications. This experimental platform serves as a critical tool for evaluating the real-world performance and feasibility of the GIS digital twin model and associated methodologies.

4.1. GIS Simulation Modeling

In this paper, a GIS-based simulation experiment platform has been meticulously constructed, as illustrated in Figure 7. This platform is designed to introduce electromagnetic wave signals from external sources, effectively simulating partial discharge events. The GIS pipe used in this setup has a shell with a diameter of approximately 560 mm, an internal coaxial conductor with a diameter of approximately 160 mm, and is sectionally pressurized to facilitate the testing process.

Fig. 7. GIS PD experimental platform.

The simulated GIS pipeline was modeled using the modeling methodology of this paper and its digital twin model is shown in Figure 8. The tester installs six external UHF sensors at the unshielded flange in accordance with the intelligently guided position.

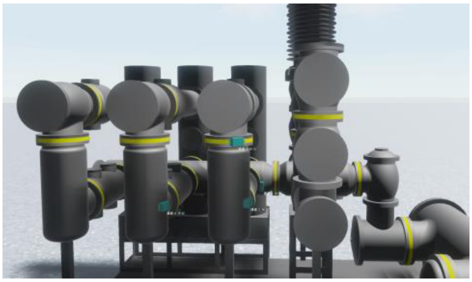
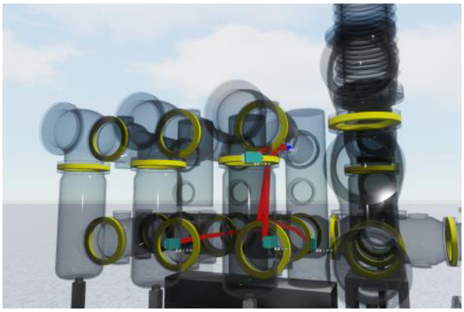


Fig. 8. GIS digital twin model.

4.2. Simulation Experiment Results

In the experimental setup, the tester employs a lighter to introduce electromagnetic wave signals at the T-corner, effectively simulating partial discharge events occurring inside the GIS pipeline. The experimental results, depicted in Figure 9, display real-time PRPD (Phase-Resolved Partial Discharge) spectra at each UHF sensor installation location. Importantly, the shortest propagation path from the partial discharge source to each UHF sensor is accurately captured and depicted in the results. This data serves as a reference benchmark, aligning with the experimental expectations and providing a foundation for the subsequent achievement of automatic localization within the GIS pipeline.

(a) PRPD pattern reslut. (b) Positioning results.

Fig. 9. Experimental results graph.

5. Conclusion

In summary, this paper presents several key contributions:

GIS Digital Twin Modeling Method: The paper introduces a novel GIS digital twin modeling approach tailored for partial discharge detection. This method enables the determination of whether a partial discharge event is situated within or outside the GIS digital twin model.

Optimized UHF Sensor Deployment Scheme: By analyzing the spatial relationship between partial discharge sources and sensors, the paper devises an optimized UHF sensor deployment scheme. This scheme serves as a practical guide for operation and maintenance personnel, aiding them in accurately positioning UHF sensors.

Experimental Validation: The effectiveness of the proposed GIS digital twin modeling method is rigorously verified through a series of simulation experiments. These experiments provide empirical evidence of the method's utility and reliability in practical applications.

Together, these contributions collectively enhance the capabilities of GIS-based partial discharge live test, streamlining the detection process, improving localization accuracy, and facilitating informed decision-making for maintenance and operation personnel.

References

[1] Yin Kaiyang, Wang Yanhui, Liu Shihai, Li Pengfei, Xue Yaxu, Li Baozeng, Dai Kejie. GIS Partial Discharge Pattern Recognition Based on Multi-Feature Information Fusion of PRPD Image. Symmetry, 2022, 14(11):2464-2464.

[2] Zheng Jianfeng, Chen Zhichao, Wang Qun, Qiang Hao, Xu Weiyue. GIS Partial Discharge Pattern Recognition Based on Time-Frequency Features and Improved Convolutional Neural Network. Energies, 2022, 15(19):7372-7372.

[3] Lu Yao, Qiu Zhibin, Liao Caibo, Zhou Zhibiao, Li Tonghongfei, Wu Zijian. A GIS Partial Discharge Defect Identification Method Based on YOLOv5. Applied Sciences, 2022, 12(16):8360-8360.

[4] Jing Qianzhen, Yan Jing, Lu Lei, Xu Yifan, Yang Fan. A Novel Method for Pattern Recognition of GIS Partial Discharge via Multi-Information Ensemble Learning. Entropy, 2022, 24(7):954-954.

[5] Wang Yanxin, Yan Jing, Ye Xinyu, Qi Zhenkang, Wang Jianhua, Geng Yingsan. GIS partial discharge pattern recognition via a novel capsule deep graph convolutional network. IET Generation, Transmission & Distribution, 2022, 16(14):2903-2912.

[6] Jing Qianzhen, Yan Jing, Wang Yanxin, He Ruixin, Lu Lei. A novel differentiable neural network architecture automatic search method for GIS partial discharge pattern recognition. Measurement, 2022, 195.

[7] Zhou, Kun, Oh, Sung Kwun, Qiu, Jianlong. Design of Ensemble Fuzzy-RBF Neural Networks Based on Feature Extraction and Multi-feature Fusion for GIS Partial Discharge Recognition and Classification. Journal of Electrical Engineering & Technology, 2021(prepublish):1-20.

[8] Wang Yanxin, Yan Jing, Yang Zhou, Wang Jianhua, Geng Yingsan. A novel 1DCNN and domain adversarial transfer strategy for small sample GIS partial discharge pattern recognition. Measurement Science and Technology, 2021, 32(12).

[9] Liu Tingliang, Yan Jing, Wang Yanxin, Xu Yifan, Zhao Yiming. GIS partial discharge pattern recognition based on a novel convolutional neural networks and long short-term memory. Entropy, 2021, 23(6).

[10] Yanxin Wang, Jing Yan, Zhou Yang, Yiming Zhao, Tingliang Liu. Optimizing GIS partial discharge pattern recognition in the ubiquitous power internet of things context: A MixNet deep learning model. International Journal of Electrical Power and Energy Systems, 2021, 125:106484-106484.

[11] Bramann Horst, Rockmann Hartmut, Zhang Yu Xiao, Yandamuri Sai. Thixomolding of Magnesium - Efficient Process Industrialization by Combining a Digital Twin and Systematic Casting Trials. Solid State Phenomena, 2023, 6904.

[12] Zang Yiming, Qian Yong, Wang Hui, Xu Antian, Zhou Xiaoli, Sheng Gehao, Jiang Xiuchen. A novel optical localization method for partial discharge source using ANFIS virtual sensors and simulation fingerprint in GIL. IEEE Transactions on Instrumentation and Measurement, 2021, 70.

[13] Robles Julia, Martín Cristian, Díaz Manuel. OpenTwins: An open-source framework for the development of next-gen compositional digital twins. Computers in Industry, 2023, 152.

[14] Xia Jingyan, Huang Ruyi, Chen Zhuyun, He Guolin, Li Weihua. A novel digital twin-driven approach based on physical-virtual data fusion for gearbox fault diagnosis. Reliability Engineering and System Safety, 2023, 240.

[15] Haynes Patrick, Yang Sheng. Supersystem digital twin-driven framework for new product conceptual design. Advanced Engineering Informatics, 2023, 58.

[16] Adu-Amankwa Nana Akua N., Pour Rahimian Farzad, Dawood Nashwan, Park Chansik. Digital Twins and Blockchain technologies for building lifecycle management. Automation in Construction, 2023, 155.

[17] Maheshwari Pratik, Kamble Sachin, Belhadi Amine, Venkatesh Mani, Abedin Mohammad Zoynul. Digital twin-driven real-time planning, monitoring, and controlling in food supply chains. Technological Forecasting & Social Change, 2023, 195.