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Digital Twin-Based Identification of Effective Partial Discharge Signals for GIS

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Abstract. In the actual substation complex environment, in addition to the influence from the environmental noise, the Gas Insulated Switchgear (GIS) online monitoring system will also receive the interference from the invalid partial discharge signal from the neighboring high-voltage equipment. Aiming at the current GIS partial discharge online monitoring system can not identify the defects of effective PD signals, combined with the advantages of digital twin technology, this paper carries out a study on the identification of effective PD signals of GIS based on digital twins, proposes a digital twin-based judgment mechanism for effective PD signals of GIS, establishes a typical digital twin model of GIS, and analyzes the decay rate of the UHF signals in the various components, based on the theoretical signal decay and actual signal decay. According to the comparison between the theoretical signal attenuation and the actual signal attenuation to determine whether the partial discharge signal is from the target high-voltage equipment, the effectiveness of this paper's algorithm is verified through simulation experiments.

Keywords: Digital Twin; External Partial Discharge; Anti-interference Technology; Partial Discharge; Target Identification.

1 Introduction

The purpose of GIS anti-interference technology is to accurately diagnose partial discharge phenomena in GIS despite the presence of environmental noise or other interference [1]. The successful application of this technology can enhance the monitoring and diagnostic capabilities of GIS equipment, reduce false alarm rates, minimize misdiagnosis rates, and offer more reliable guidance for equipment operation and maintenance [2]. The precise diagnosis and monitoring of partial discharge phenomena in GIS enable the early detection of potential faults, the implementation of appropriate repair and maintenance measures, and the assurance of equipment safety and reliability [3]. Simultaneously, the development of effective anti-jamming technology can bolster the anti-jamming capabilities of GIS equipment, ensuring its accurate identification of partial discharge phenomena in complex electromagnetic environments [4].

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In practical substation complex environments, besides the influence of environmental noise, the GIS online monitoring system may also encounter interference from invalid partial discharge signals [5-8]. Invalid partial discharge signals pertain to those generated by certain high-voltage equipment near the target GIS equipment [9]. While these signals are indeed indicative of partial discharge, they must be filtered out as interfering signals when monitoring the current GIS equipment. Failure to do so could lead to frequent misdetection issues [10].

Digital twin technology is an emerging innovation within the electric power industry that facilitates real-time monitoring, predictive analysis, and optimization decision-making for substation operation [11]. Consequently, this transformation substantially enhances operational efficiency and equipment reliability within the power industry [12-15].

Due to current limitations of GIS partial discharge online monitoring systems, it cannot efficiently identify partial discharge signal anomalies. This paper aims to leverage digital twin technology to address this challenge. The aim is to develop a methodology for identifying effective partial discharge signals within GIS. To achieve this, a digital twin framework tailored to the detection of effective partial discharge signals in GIS is proposed. This framework involves the creation of a representative digital twin model for GIS, shedding light on the mechanism behind the identification process.

Moreover, this study delves into the attenuation rates of ultra-high-frequency signals across different components of the grounding system. By comparing the theoretical signal attenuation with observed signal attenuation, the study seeks to ascertain whether a given signal originates from the intended high-voltage equipment and is indicative of partial discharge events. The effectiveness of this algorithm is then validated through a series of simulation experiments.

2 Effective partial discharge signal and digital twin analysis

2.1 GIS external partial discharge signal analysis

During practical operation, the GIS online monitoring system may confront interference caused by partial discharge signals emanating from neighboring high-voltage equipment. This paper underscores the importance of effectively discerning genuine partial discharge signals through the following illustrative instances.

To illustrate this significance, we will consider the case of a 550kV substation. Specifically, we focus on the 220kV GIS equipment within this substation, which is equipped with a UHF partial discharge online monitoring system. The layout of this equipment is depicted in Figure 1.

In the routine operation of this GIS equipment, the GIS online monitoring system detected an alarm triggered by an abnormal PRPD (Partial Discharge Pattern Recognition) spectrogram. The PRPD pattern is visually represented in Figure 2. The x-axis indicates the discharge phase, the y-axis indicates the discharge amplitude, and the color changes from green to yellow to red, indicating that the number of discharges is getting denser. Upon conducting initial pattern recognition, the system identified the nature of the partial discharge as being tip discharge. Consequently, the system flagged this event as a partial discharge occurrence within the GIS equipment, prompting an alarm to be issued to the operational and maintenance personnel.

Fig.1 GIS Equipment Distribution

However, upon further investigation and source localization, it was determined that the anomalous signal, in fact, emanated from different intervals along the same row of busbars. Each interval was equipped with external UHF sensors, and as a consequence, the signal affected various intervals to varying degrees, leading to the generation of multiple false alarms. This situation resulted in a substantial increase in the false detection rate and significantly augmented the troubleshooting workload for the operational and maintenance personnel.

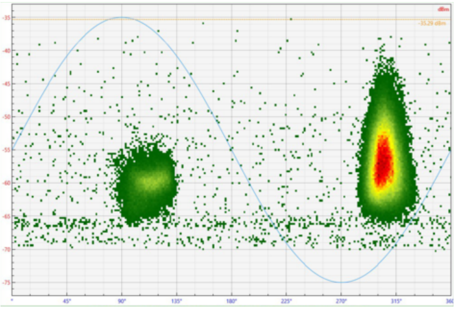

Fig.2 PRPD Pattern

In this scenario, the GIS online monitoring system's inability to differentiate between valid and invalid partial discharge signals resulted in the generation of unwarranted alarms. Therefore, it is of paramount importance to precisely distinguish valid partial discharge signals and ascertain whether their sources indeed originate from within the targeted GIS equipment.

2.2 Digital Twin technology

Digital twin technology is gaining significant prominence as a novel approach that intricately merges the physical and virtual realms to achieve real-time synchronization, high-precision simulations, and efficient decision-making within systems [16].

In the realm of substation equipment operation and maintenance, digital twin technology offers several noteworthy advantages [17]. Firstly, it enables real-time synchronization and precise simulation of equipment status, effectively enhancing the efficiency and reliability of equipment operation. Secondly, through real-time predictions of equipment condition and optimization decision-making, it substantially reduces the likelihood of equipment failures and prolongs the equipment's service life. Furthermore, digital twin technology facilitates the transition from traditional manual inspection and maintenance methods to digitalization and automation in equipment operation and maintenance practices, leading to a significant improvement in operational and maintenance efficiency.

3 Digital Twin Based Judgment Mechanism of Effective Partial Discharge Signal for GIS

To address the challenges outlined above, and leveraging the capabilities of digital twin technology, this paper conducts an investigation into the identification of valid partial discharge signals within GIS. The study introduces a mechanism for discerning effective partial discharge signals within GIS, grounded in the principles of digital twin technology. Specifically, a digital twin model for GIS is established, and an analysis of the attenuation rates of ultra-high-frequency signals is conducted. This analysis serves as a basis for determining whether a signal originates from within the interior of the GIS equipment, relying on the ratio between the theoretical attenuation rate and the observed attenuation rate.

3.1 GIS digital twin modeling

3.1.1 Modeling methodology

In this paper, Solidworks software has been selected as the tool for constructing the digital twin model. It involves meticulous 3D modeling of GIS equipment, which is achieved by referencing GIS drawings and on-site measurements. It is worth noting that the primary focus during the construction of the digital twin model in this study is geared towards the practical requirements of online partial discharge detection.

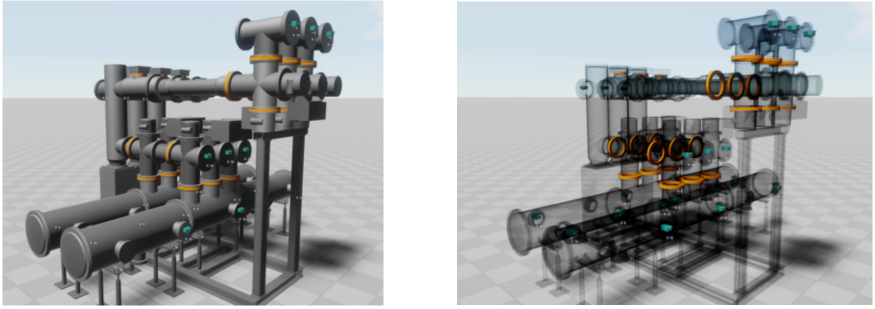
(a) external model (b) internal model

Fig.3 Digital Twin Model

Consequently, the modeling process primarily emphasizes the external shell of the GIS pipe, with a thickness of 0.001 m, while the interior of the pipe is left empty. This approach implies that, at this stage, the internal structure of the GIS, and its potential impact on the propagation delay of UHF signals, is temporarily disregarded. The resulting digital twin model, as depicted in Figure 3, effectively encapsulates the key attributes of the GIS equipment in a visually intuitive manner, thereby facilitating the operational and maintenance tasks of field testers.

3.1.2 Signal attenuation of each component

The propagation of UHF signals within the GIS pipeline exhibits significant variations in signal attenuation due to differing degrees of attenuation associated with various GIS components. Consequently, when a partial discharge event occurs closer to a sensor, the received signal strength may be lower than when the discharge source is farther away from the sensor. This variability in signal strength is a key factor that complicates the localization of the discharge source. Relying solely on signal strength comparisons for GIS partial discharge source localization becomes challenging under these conditions.

Table 1 outlines the attenuation characteristics of each component for specific models of GIS. It is crucial to note that the signal attenuation characteristics can differ for GIS equipment from various manufacturers, voltage levels, and models. Hence, precise real-world measurements are indispensable for each specific case to account for these variations.

Table1 Average Attenuation of Each Component

GIS Component Model	Average Attenuation
500kV GIL bus	4dB/100m
500kV GIS bus	5dB/100m
Compact GIS bus	7dB/100m
1000kV GIS insulated basin	3dB
500kV GIS insulated basin	2.5dB
Compact GIS insulated basin	2dB
500kV、1000kV circuit breaker	15dB
220kV、110kV circuit breaker	12dB
GIS T-joint	6dB
GIS arc-shaped corner	4dB
GIS right-angle corner	6dB

In practical implementation, we have developed signal attenuation models for each component within the digital twin model. These models are based on the inherent attenuation characteristics of each GIS component and are primarily represented as attenuation coefficients per unit length, typically over a distance of 0.1 meters. For instance, the attenuation coefficient for the 500kV GIS pipeline is 0.005 dB, while the attenuation coefficient for the 500kV GIS insulating basin (with a thickness of 0.1 meter) is 2.5 dB, and so on.

Subsequently, these attenuation coefficients are assigned to each of the coordinate points within the digital twin model. This enables the simulation of signal propagation characteristics, accounting for the specific attributes of each GIS component, thus facilitating a comprehensive understanding of signal behavior within the system.

3.2 Theoretical attenuation rate calculation for UHF signals

Upon completing the GIS digital twin modeling, the next step involves the theoretical attenuation rate calculation from the partial discharge source to each UHF sensor. This calculation is essential to determine whether the partial discharge source resides within the GIS, signifying whether the signal qualifies as an effective partial discharge signal.

Let's assume that the partial discharge source is situated on the line side of the circuit breaker. The signal path from the discharge source to Sensor A on the bus is as follows: "Discharge source - Circuit breaker - Current transformer - Disconnect switch - Bus - Sensor A." The theoretical transmission attenuation can be calculated using the following equation:

TA= Circuit breaker attenuation factor x circuit breaker length + right-angle corner attenuation factor x length of the right-angle corner below the circuit breaker + current transformer attenuation factor x length of the current transformer + disconnect switch attenuation factor x length of the disconnect switch at the bus + right-angle corner attenuation factor x length of the right-angle corner at the bus + bus attenuation factor x length of transmission along the bus.

Assuming that Sensor A is positioned within the bus interval, the transmission path to Sensor B located at the end of the line is as follows: "Discharge power - Circuit breaker - Current transformer - Disconnecting switch - Bus - Sensor A." The theoretical transmission attenuation can be calculated as follows:

TB= current transformer attenuation factor x current transformer length + disconnect switch attenuation factor x line disconnect switch length + T-connection attenuation factor x T-connection corner length at the disconnect switch + line terminal barrel attenuation factor x line terminal barrel length.

These calculations provide insights into the expected signal attenuation along different paths, aiding in the determination of whether the partial discharge source is located inside the GIS, thereby identifying valid partial discharge signals.

3.3 Judgment of effective partial discharge signals

Following the completion of the theoretical attenuation rate calculations for the UHF signal and the subsequent comparison with the actual attenuation rate, it becomes possible to ascertain whether the signal source is located within the GIS, effectively distinguishing between valid and invalid signals.

Let's consider a scenario in which the partial discharge source is positioned on the line side of the circuit breaker, and its signals are transmitted to both Sensor A on the bus and Sensor B at the line termination. The theoretical transmission attenuation for each sensor has been previously computed.

Assuming that theoretically, the difference in signal amplitude received by Sensor A and Sensor B should be (TA - TB), and in practice, the observed difference in signal amplitude received by Sensor A and Sensor B is (RA - RB), a threshold value, Th, is set. If $|(TA - TB) - (RA - RB)| > Th$, then the partial discharge signal is deemed to originate from outside the GIS.

This recognition mechanism empowers the effective identification and exclusion of invalid partial discharge signals, even within complex environments. Consequently, it enhances the accuracy of condition assessment for GIS equipment, facilitating more efficient monitoring and maintenance practices.

4 Simulation experiment analysis

In this chapter, we establish a GIS simulation experiment platform to validate the effectiveness of the partial discharge signal identification method proposed in this paper. We achieve this validation through a series of simulation experiments conducted on the platform.

4.1 GIS Simulation Modeling

To conduct empirical investigations, this paper establishes a GIS-based simulation experiment platform, as illustrated in Figure 4. Within this experimental platform, UHF signals resulting from partial discharges are simulated by injecting electromagnetic wave signals. This simulation approach allows for a more realistic representation of partial discharge scenarios, facilitating the validation of the external partial discharge signal recognition algorithm. The platform also enables the step-by-step pressurization of the cavity, thereby simulating various degrees of partial discharge and enhancing the breadth of experimental conditions.

Fig.4 GIS PD experimental platform

The simulated GIS pipeline was constructed using the modeling approach outlined in this paper, resulting in the creation of its digital twin model, as depicted in Figure 5. During the experiment, the tester strategically positions an external UHF sensor at the unshielded flange in accordance with intelligent guidance.

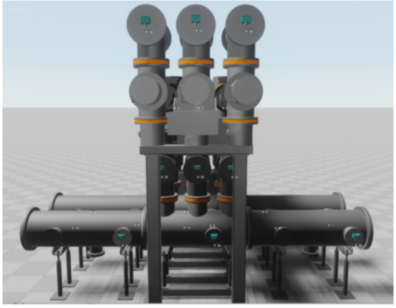

Fig.5 GIS Digital Twin Model

4.2 Simulation experiment analysis

During the experiment, the tester employs a lighter to inject an electromagnetic wave signal at the T-corner, simulating a scenario where partial discharge occurs inside the GIS pipeline. The outcomes of this experiment are illustrated in Figure 6, with each UHF sensor installation location displaying real-time PRPD spectra. The blue lightning mark represents the localized position of the partial discharge source.

Based on the localization results for the partial discharge source, it can be deduced that the signal is indeed valid and originates from within the GIS equipment's interior. This outcome aligns with the experimental findings, confirming the effectiveness of the signal identification approach.

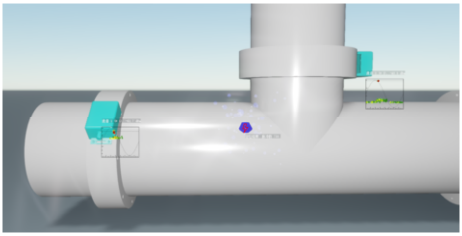

Fig.6 Experimental results

In another experiment, the tester utilizes a lighter to inject an electromagnetic wave signal outside the pipeline, simulating a scenario where partial discharge takes place outside the GIS pipeline. The outcomes of this experiment are presented in Figure 7, with each UHF sensor installation location displaying real-time PRPD spectrograms exhibiting distinct partial discharge characteristics.

However, it's important to note that there is no display of partial discharge source localization in this case. The signal is consequently deemed invalid and attributed to external interference, which aligns with the experimental results. This confirms the method's ability to effectively exclude and identify external interference signals.

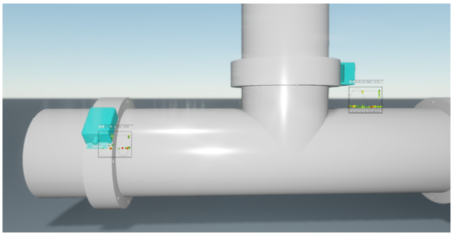

Fig.7 Experimental results

5 Conclusion

1) The paper conducts research on the identification of valid partial discharge signals in GIS using digital twins. It presents a mechanism for discerning effective partial discharge signals within GIS based on digital twins and establishes a representative digital twin model of GIS.

2) The study includes an analysis of the attenuation rates of UHF signals within GIS. It introduces an effective mechanism for identifying valid partial discharge signals by comparing the theoretical attenuation rate with the actual attenuation rate.

3) To validate the efficacy of the GIS effective partial discharge identification method proposed in this paper, a GIS simulation experiment platform is meticulously constructed. This platform serves as a foundation for conducting simulation experiments, providing empirical evidence of the method's effectiveness.

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