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Application of Digital Twin Technology in Substations: High Voltage Reactor Meter Visual Field Analysis of Phase A

Wei He, Huarui Xiao, Lianghong Lv, Di Wang

Northeast Electric Power Design Institude Co., Ltd. Of China Power Engineering, Changchun, China

Abstract

This paper explores the application of Digital Twin (DT) technology in the monitoring and maintenance of high-voltage reactor meters within substations. Traditional inspection methods face limitations in covering the extensive areas and complex structures within substations, which DT technology can address by providing real-time monitoring, predictive analytics, and data-driven insights. The study focuses on visual field analysis for optimizing camera placement and configuration around high-voltage reactors, enhancing inspection accuracy and operational efficiency. Key components include IoT sensors, real-time analytics, and advanced visualization techniques. The findings suggest that DT-enabled systems significantly improve the reliability, safety, and efficiency of substation management, demonstrating potential for broader smart grid applications.

Keywords

Digital Twin; Substation; High Voltage Reactor Meter; Visual Field Analysis; Predictive Maintenance.

1. Introduction

As substations form crucial nodes within the power grid, ensuring continuous, accurate, and efficient monitoring of high voltage reactors and meters is essential. Traditional inspection methods often fall short in high-voltage settings due to the extensive areas involved, the high number of components, and the risks to personnel. Digital Twin technology, with its capacity to create virtual replicas of physical assets, allows for real-time monitoring, predictive analytics, and data-driven insights. This paper focuses on the DT-enabled visual field analysis of high voltage reactor meters, aiming to enhance inspection accuracy and optimize operational procedures within substations.

2. Digital Twin in High Voltage Reactor Meter Monitoring

Digital Twins in substations function by mapping real-time sensor data to a dynamic virtual model of the high voltage reactor meter. This model simulates the physical conditions of the asset, providing detailed insights into the operational state of meters and aiding in the detection of anomalies. Key components of the DT system for meter monitoring include:

2.1. Sensors and Data Collection

IoT sensors placed around high voltage reactors gather data on meter readings, environmental parameters, and visual coverage.

2.2. Real-time Analytics and AI

Data analytics models interpret sensor data, providing alerts on irregular readings and generating predictive insights.

2.3. Visualization

A 3D model displays real-time data, showing the visual field of each meter to ensure full observational coverage.

3. High Voltage Reactor Meter Visual Field Analysis

The visual field analysis in a DT-enabled high voltage reactor meters in substation focuses on optimizing the placement and configuration of cameras around high voltage reactors. This includes: Resolution and Field of View Adjustment, Simulation of Obstructions, Camera Placement Optimization and Visual Field Analysis.

3.1. Resolution and Field of View Adjustment

Adjusting camera resolutions and fields of view to ensure that meters remain within sight under various environmental conditions.

3.2. Simulation of Obstructions

The digital twin system simulates potential obstructions (e.g., weather or equipment) that could obscure meter visibility, adjusting the system configuration as needed.

3.3. Camera Placement Optimization

According to the position and orientation of the meter, select the camera that can observe the meter, and render a field of view of the camera at the current Angle according to the camera parameters, which can directly reflect whether the meter can be observed.Determining ideal camera locations for high voltage reactor to capture meter readings based on their positions and orientations.Taking the high voltage reactor phase A area meters as an example, the figure is represented by the Red mark to analyze whether the area meter can be observed by the camera.

3.4. High Voltage Reactor Meter Visual Field Analysis of Phase A

3.4.1. Visual Analysis of Phase A Meter 1

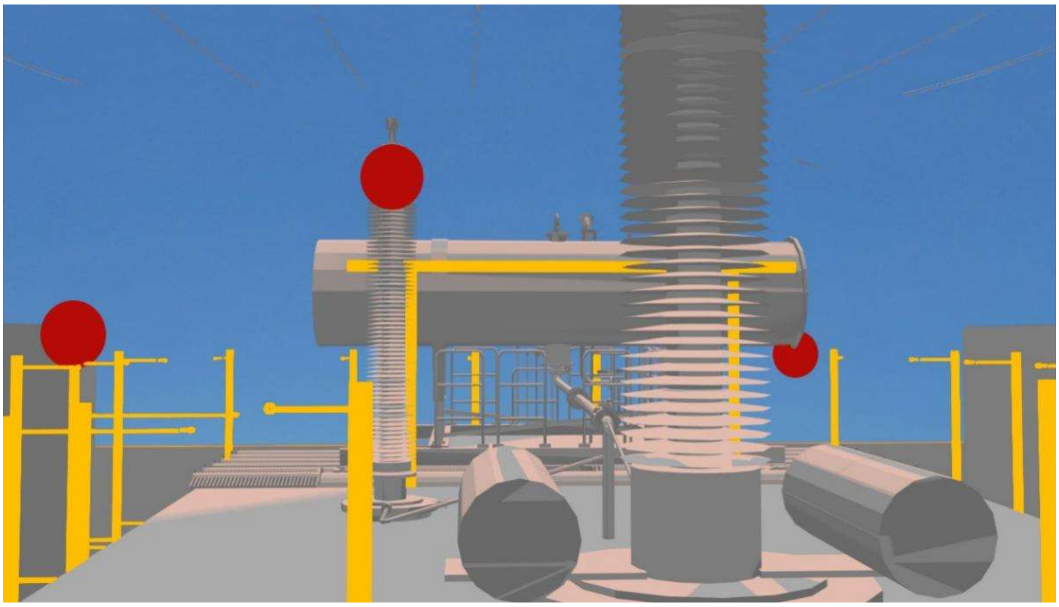

Figure 1. Pan-Tilt Camera 1 Field of View Diagram

The pan/tilt camera 2 is at an angle greater than 90° from the direction of Phase A Meter 1, making it impossible to observe the meter. Since the ball machine 4 has a larger observation angle with the meter, the pan/tilt camera 1 is directly facing the meter. Therefore, visual analysis is conducted using the pan/tilt camera 1, and the distance from the pan/tilt camera 1 to the meter is 17.6032 m. The resolution of the pan/tilt camera 1 is 1920*1080, resulting in a high-magnification observation of the meter by the pan/tilt camera 1 as shown in Figure 1, where the horizontal field of view angle of the pan/tilt camera 1 is 39.7° and the vertical field of view angle is 29.6°.

3.4.2. Visual Analysis of Phase A Meter 2

There is obstruction between the pan/tilt camera 1, ball camera 4, and Phase A meter, making it impossible to observe the Phase A meter. The distance between the pan/tilt camera 2 and the Phase A meter is 18.9962 m. The resolution of the pan/tilt camera 2 is 1920*1080, resulting in the high-magnification observation of the meter shown in Figure 2, where the horizontal field of view angle of the pan/tilt camera 2 is 44.2° and the vertical field of view angle is 31.3°.

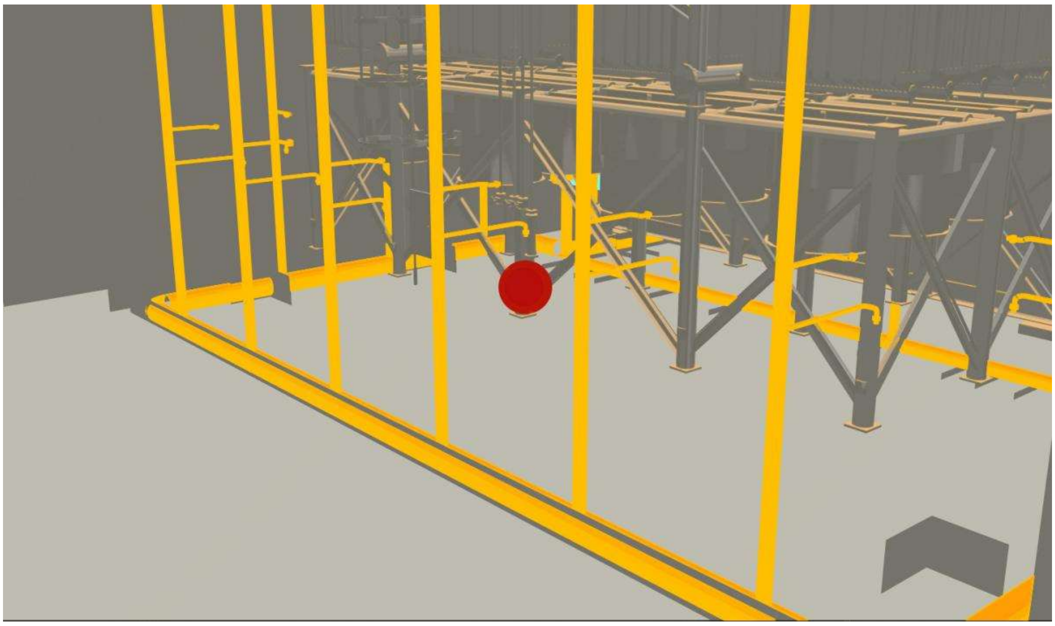

Figure 2. View of the pan-tilt camera 2

4. Literature References

Digital twin visual field analysis significantly enhances predictive maintenance in complex manufacturing processes by creating a dynamic, real-time digital representation of physical assets. This technology leverages data from sensors and advanced analytics to predict equipment failures, optimize maintenance schedules, and improve overall system reliability. By integrating digital twins with predictive maintenance strategies, manufacturers can achieve better asset utilization, reduce downtime, and enhance operational efficiency. The following sections detail how digital twin visual field analysis contributes to these improvements.

4.1. Real-Time Condition Monitoring

Digital twins enable continuous monitoring of equipment by replicating physical objects in the digital space, allowing for real-time condition assessment and anomaly detection[1,2]. The integration of IoT and cloud computing facilitates the collection and analysis of sensor data, providing insights into the health and performance of manufacturing systems[1]. In the automotive industry, digital twins have been used to monitor vehicle components, enhancing reliability and safety through real-time data analysis[3].

4.2. Predictive Analytics and Machine Learning

Machine learning algorithms, such as deep learning and autoencoders, are employed within digital twins to analyze historical and real-time data, predicting potential failures before they occur[4,5].These predictive models can forecast the remaining useful life of equipment, allowing for timely maintenance interventions and reducing unexpected breakdowns[2]. In a case study involving conveyor belts, digital twins demonstrated high precision in fault prediction, showcasing the effectiveness of machine learning-based predictive maintenance[5].

4.3. Optimization of Maintenance Strategies

Digital twins support the development of cost-effective and reliability-centered maintenance frameworks by providing qualitative and quantitative analysis of monitoring data[6]. The ability to visualize and simulate the impact of maintenance decisions in a digital environment aids in refining maintenance strategies and improving decision-making processes[7].

4.4. Enhanced System Reliability and Efficiency

The use of digital twins in predictive maintenance leads to improved system reliability by minimizing downtime and extending the lifespan of equipment[4]. In complex manufacturing processes, such as die-casting, digital twins facilitate real-time quality prediction and defect detection, enhancing product quality and manufacturing efficiency[8]. The integration of digital twins with AI and machine learning enhances the accuracy and effectiveness of predictive maintenance solutions, contributing to the overall efficiency of manufacturing systems[3].

5. Conclusion

The application of Digital Twin technology in transformer meter monitoring within substations presents substantial improvements in operational efficiency, safety, and reliability. Although challenges remain, the benefits of real-time monitoring, predictive maintenance, and comprehensive data integration make DT a promising solution for substation management. As technology advances, DT systems are expected to become integral to the safe and efficient operation of substations, paving the way for future innovations in smart grid management and energy infrastructure.

While digital twin technology offers substantial benefits for predictive maintenance, it is still an emerging field with challenges such as standardization and implementation methodologies. The development of robust architectural frameworks and feedback mechanisms is crucial for maximizing the potential of digital twins in manufacturing. Additionally, the integration of digital twins with existing systems requires careful consideration of data security and interoperability issues. As the technology evolves, addressing these challenges will be essential to fully realize the transformative potential of digital twins in predictive maintenance.

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