MATEC Web of Conferences **401**, 10006 (2024) https://doi.org/10.1051/matecconf/202440110006
ICMR2024

Digital Twin Framework for Solar Power Plants in Kazakhstan

Gani Kazbek[1], *Shyndaulet* Kassymkhanov[2], *Yerassyl* Alipov[1], *Nurbek* Meiirbekov[1], *Altay* Zhakatayev[1], and *Essam* Shehab[1*]

[1]Mechanical and Aerospace Engineering Department, School of Engineering and Digital Sciences, Nazarbayev University, Astana, Kazakhstan
[2]TechnoGroupService (TGS), Almaty, Kazakhstan

Abstract. This paper aims to present a detailed Digital Twin (DT) framework indicating important implementation steps and providing insights into DT technology that improves operational efficiency, optimizes performance, and creates a user-friendly platform for real-time monitoring. This project is conducted in collaboration with TechnoGroupService (TGS) company, which specializes in constructing, operating, and maintaining solar and wind power plants in Kazakhstan. The development of DT framework was performed in four phases: project formulation and planning; conducting literature review and analysing the operational processes data transfer procedures of the 50 MW solar power plant; identifying the required specifications of the framework; the development of DT framework and implementation roadmap along with the development of a fully functional prototype. A detailed investigation of the 50MW solar power plant's operational processes, equipment and sensors, communication networks and data models was performed. The developed framework provides a DT architecture with several layers, including physical infrastructure, data model, modelling and application of DT. Finally, the developed prototype is a handful tool for real-time monitoring and reactive maintenance of the power. The further applications of DT include predictive maintenance and power output forecasting. The obtained results have been reviewed by industry experts to ensure applicability and reliability.

1 Introduction

Several countries followed the trend of digital transformation and launched their strategies such as “Industry 4.0” in Germany, “Society 5.0” in Japan, “Made in China 2025” in China, and more generally “The Factory of Future” in Europe [1]. The term "digital twin" refers to a real-time and virtual representation of a physical object, system, or process. Digital twin (DT) technology has developed as an innovative tool and is a dynamic digital copy that serves to emulate physical assets and real-world processes. DTs, which were originally developed in the manufacturing sector, then spread to other industries, including the energy sector. This

[*] Corresponding author: essam.shehab@nu.edu.kz

section explains the basic idea behind the DT technology. The fundamental insight into the progress of DTs can be gained by following their historical development from conception to broad adoption. Since their inception in the 2000s, DTs have progressed from simple simulations of real processes to complex, data-driven models that enable various businesses to maximize efficiency, reduce hazards, and simplify the decision-making process [2]. As a result, a DT in the energy industry is a virtual replica of actual power systems, processes, and equipment that can carry out computer modeling, simulation, intelligent data analysis, and machine learning tasks to help users improve conventional electric grid planning and decision-making processes [3]. To deliver a meaningful response to the complex problems faced by the power grid systems, the DT has developed modeling, simulation, and optimization capabilities. DT serves both visual and predictive purposes for the electric grid. It may also be used to forecast its expected behavior. The real-time data collection, transmission, and processing can also be accomplished by the virtual model [4].

The goal of DT is to offer accurate information on the physical twin without relying on modelling or simulation of the system behaviour [5]. Noteworthy are the important developments in cyber-physical systems, the Internet of Things (IoT), and artificial intelligence that are presented as novel revolutions in smart power plants. In addition to these technologies, real-time data is constantly gathered, handled, and evaluated to produce a digital representation of a physical system and a precise understanding of its present and potential future states. As a result, the precise, dynamic, and contemporary virtual representation of the intended system is prepared for efficient real-time analysis and control. Real-time and historical data can be handled safely and effectively with the help of a DT power system. This system also helps with maintenance, design, and operation management. Since DT-based power systems are novel and intricate in concept, research on them is still in its early phases.

However, the manufacturing sector has employed the DT technology to monitor and control the conditions of its products and production lines [6, 7]. The literature review revealed that there is a lack of research regarding the DT technology and its application in Kazakhstan's solar power plants. Due to the difference in solar power plant scale and operating environment, the existing literature does not provide information on the operational processes of Kazakhstan's solar power plants. Such information is crucial since it provides a foundation for future digital twin platform applications. The plant's facilities, scale, equipment, and hardware are essential components for digital twin. Without a comprehensive understanding of various plant processes, it is challenging to develop effective digital twin models tailored to the local context.

2 Research Methodology

This research work was carried out in collaboration between the School of Engineering and Digital Sciences, Nazarbayev University, Kazakhstan and TechnoGroupService (TGS) company, which specializes in constructing and operating solar power plants in Kazakhstan. Therefore, a research methodology that satisfies the needs of both industry and academia has been employed. The methodology comprises four integrated phases. The first phase was to formulate the project and carry out project planning. The second phase was to concurrently conduct a literature review and analyse the operational processes and data transfer procedures of a solar power plant with the Techno Group Service (TGS) company to identify the required specifications of the framework. The third phase involved the development of the DT framework, implementation roadmap and the DT prototype. The fourth phase involved expert's validation, gathering feedback and defining future work and improvements of the DT framework and the prototype. Prototype development employed the current infrastructure and real-time data integration to simulate the operations of the solar power plant on a digital platform.

3 Findings

3.1 Solar Plant Analysis

This section describes a 50 MW solar power plant located in Kazakhstan and the plans to create a DT of the plant to monitor and improve its performance. The DT is a computer-based digital model that mirrors the real plant and allows engineers to test changes and troubleshoot problems without affecting the actual equipment. The plant uses solar panels to convert sunlight into electricity. It has a total power output of 50 MW, and it uses 94,150 solar panels. The plant produces about 83 million kWh of electricity per year.

The electricity is generated in PV modules, collected in strings (1 string has 50 modules) and transferred to the combiner boxes. All combiner boxes are connected to the block building, where the inverters are located. An inverter transfers the current from DC to AC to be further transmitted to the grid through the transformers.

The data flows from the solar panels across all the components to the control room and external recipients. The data is then sent to a local network storage and then to the control room, where it is monitored by operators. The plant uses fiber optic cables to connect the different parts of the plant together. The communication system is based on Profibus standards, which are a set of protocols for industrial automation.

The DT will need to store a large amount of data in real-tome monitoring with high frequency (1 minute). It was decided to construct a database in the following way: unique identifiers are indexes for each parameter of the power plant and a timestamp column has a one-minute update frequency to make the database more systematic with common update frequency for different parameters.

The DT will include a 2D (top view) visualization of the solar power plant. This visualization will demonstrate the exact geographical locations of all of the components of the plant, such as the solar panels, inverters, and transformers. Google Maps API was used to locate all the components in 2D view using coordinates (latitude and longitude).

3.2 Framework Development

The framework is built upon a foundation established through a review of existing literature and a comprehensive analysis of the plant's operational practices. This synergy between theoretical knowledge and real-world applications ensures the framework is not only grounded in established research but also adaptable to the specific context of Kazakhstan's renewable energy sector.

The core components of a solar power plant's DT include digital representations of solar panels, inverters, and the grid connection. The solar panel's DT precisely replicates its physical form, considering factors like size, direction, and efficiency. It also incorporates real-time weather data like solar intensity and angle of incidence to simulate the panel's behaviour under various conditions, enabling accurate power output forecasts.

Weather data plays a critical role in the DT's operation. This data encompasses information on temperature, wind speed, sunshine intensity, and other relevant weather variables. By incorporating this data, the DT can model how the solar power plant would perform under various weather scenarios. This enables accurate power output predictions and facilitates planning for periods with less sunlight.

The success of the DT hinges on the dynamic and two-way interaction between the physical plant and its digital counterpart. A network of sensors embedded within the physical plant continuously gathers data on various parameters, feeding this real-time information to the DT. This data allows the DT to maintain a constantly updated and dynamic representation of the real plant in the virtual environment.

The second stage of this interaction involves the DT transmitting control commands back to the physical plant. By leveraging its simulations and forecasts, the DT can generate control commands for various plant components. For instance, it might adjust the solar panels' orientation to maximize sunlight absorption or regulate battery charge and discharge cycles to optimize battery life. However, this functionality is not covered in this specific implementation due to the absence of actuators in the field.

This data exchange between the physical plant and the DT is continuous, not a one-time event. As the physical plant operates and undergoes changes, it generates new data that is fed back to the DT. The DT, in turn, refines its simulations and generates new control commands based on this ongoing feedback loop. Over time, this continuous learning process progressively improves the accuracy of the DT's models and forecasts.

The framework also details the model layer, which serves the purpose of data visualization and application scenario modeling in a user-friendly and interactive manner. This layer caters to real-time monitoring, reactive maintenance, and performance analytics through graphs, figures, and tables. Additionally, it supports other applications like energy forecasting and predictive maintenance.

The framework acknowledges two potential solutions for realizing the model layer's functionalities. The first approach involves developing a web platform from scratch. While the proposed database structure offers flexibility for backend development, the frontend poses a challenge due to the need for 2D plant visualization or geospatial data integration.

Alternatively, leveraging open-source software like Azure Digital Twin as a SaaS (Software as a Service) is another option. This platform provides a ready-made foundation for deploying DT solutions. However, its functionality and flexibility might be limited by the platform's capabilities, and user expertise in using such platforms could be a hurdle.

The application layer of a DT for a solar power plant uses various software, algorithms, and analytics to interpret data collected from sensors. This data provides real-time insights into the plant's performance and allows for more complex analyses like predicting power generation and identifying maintenance needs.

One key application is real-time monitoring. The DT continuously receives data, enabling close control over equipment and pinpointing deviations in power generated by individual panels. This facilitates reactive maintenance by allowing operators to quickly address issues as they arise. For instance, if a string experiences voltage fluctuations, the DT can alert operators for prompt repair.

Another important application is predictive maintenance, which uses historical data and machine learning to forecast equipment failures before they happen. This proactive approach prevents downtime, delays possible failures, reduces the number of failures, and keeps the plant running efficiently by identifying potential problems and suggesting maintenance schedules.

The framework, as shown in Figure 1, establishes a comprehensive approach for creating a DT of a solar power plant, fostering improved monitoring, optimization, and overall performance of renewable energy generation facilities.

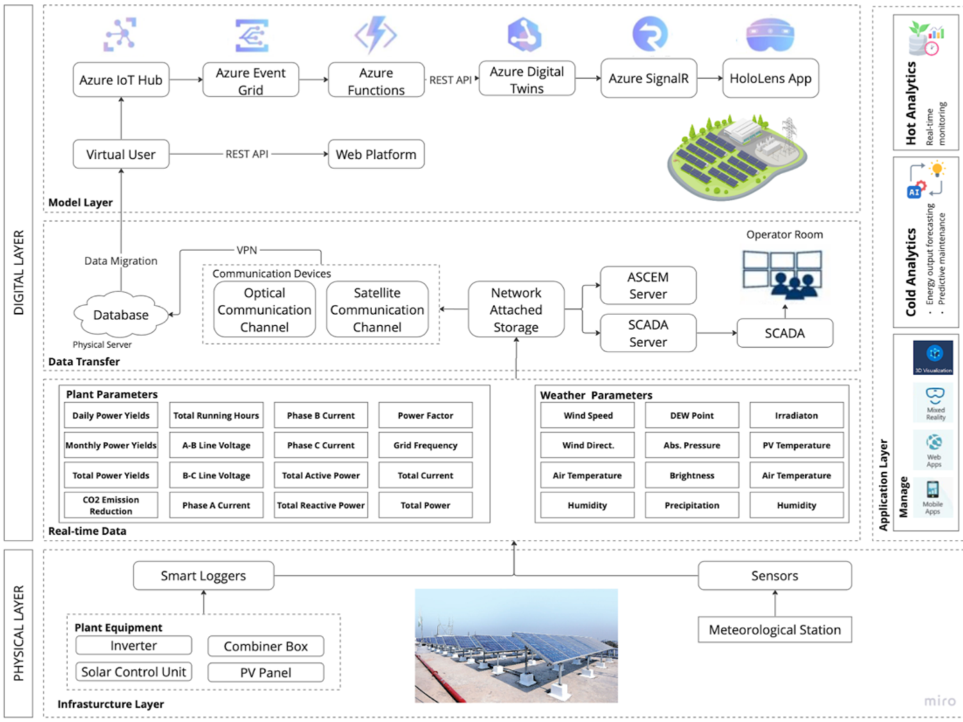

Fig. 1. The Proposed Framework for Solar Power Plant

3.3 Prototype Development

This section describes the development of a Minimum Viable Product (MVP) for the web platform component of the DT. The web platform is designed for real-time monitoring of the solar power plant.

The existing platform uses Python Flask for the backend and React for the frontend. However, the databases used by the existing platform and the digital twin are incompatible. Additionally, integrating real-time monitoring functionalities requires more complex front-end development compared to the backend.

To address these challenges, the MVP utilizes a new architecture with FastAPI for the backend (written in Python) and PostgreSQL for the database. For the frontend, React is used along with the Google Maps API to display a top view of the power plant.

The MVP includes around 185-200 data points on the 2D map of the plant, taking data from combiner boxes, inverters, and a meteorological station. Future versions could include data from individual strings, bringing the total number of data points to around 7,000. The components are shown in different colours (red, green, or purple) to visually display the status of the components.

Overall, the MVP is a functional module that demonstrates the potential of the web platform for real-time monitoring of the solar power plant. The MVP showcasts real-time data transfer with a 1-minute sampling period. Moreover, it displays general statistics for the entire station and can demonstrate specific information from a particular combiner box.

4 Conclusions

This paper described the development of DT implementation framework, detailed implementation roadmap, and DT prototype for a 50 MW solar power plant. In addition, this work described the operational procedures of a 50MW solar power plant and indicated the main aspects in terms of equipment, sensors, and IoT devices to consider for DT implementation. Moreover, the development of a Web Platform emerges as a crucial component, offering a user-friendly interface for real-time monitoring and reactive maintenance strategies. This visualization tool not only facilitates immediate decision-making but also enables stakeholders to adaptively respond to emerging issues, thereby minimizing downtime and maximizing productivity. Furthermore, the incorporation of both cold and hot analytics within the proposed DT framework presents a robust approach towards predictive maintenance and energy forecasting. By leveraging historical data and real-time insights, organizations can anticipate potential faults, mitigate risks, and optimize resource utilization, thereby enhancing overall system reliability, maintainability, and performance.

Further research effort could include the development of DT for wind power plants, cost estimation and analysis of DT for solar power plants and cybersecurity aspect of DT, which is an essential part of DT in terms of data privacy. Integration of cybersecurity measures to DT ensures the safety of sensitive data, prevents unauthorized access to it, and fends off attempts for data manipulation. By overlooking cybersecurity, this project does not focus on potential risks associated with unauthorized access and data leakage.

Acknowledgments

The authors gratefully acknowledge funding support from Nazarbayev University under the Faculty Development Competitive Research Grant Program (FDCRGP), Grant No. 11022021FD2904.

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