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3	
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Development of an artificial intelligence-based adaptive digital twin method for early fault detection and energy loss reduction in solar photovoltaic systems

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Abstract: This article examines the scientific and conceptual foundations for developing an artificial intelligence-based adaptive digital twin method aimed at early fault detection and the reduction of associated energy losses in solar photovoltaic systems. An adaptive digital twin model is proposed by integrating real-time monitoring data, environmental parameters, electrical indicators, technical condition characteristics, and time-varying operational data into a unified information environment. The model is designed to enable early detection of operational deviations, forecasting of potential fault development, assessment of their impact on energy generation, and formulation of optimal technical decisions. The scientific novelty lies in dynamically updating the virtual model and integrating the sequence of “monitoring → early anomaly detection → fault forecasting → energy-loss assessment → technical decision” into a unified adaptive digital twin architecture.

Keywords: solar photovoltaic system, digital twin, artificial intelligence, adaptive model, early fault detection, energy losses, forecasting, technical diagnostics, predictive maintenance, monitoring

1. Introduction

The expanding application of photovoltaic (PV) systems in the energy sector is making the long-term, stable, and efficient operation of such systems an increasingly important scientific and practical challenge. During real-world operation, factors such as module degradation, partial shading, soiling, thermal effects, faults in electrical connections, and failures of inverters and other components can reduce the energy generation efficiency of photovoltaic systems. Therefore, rather than assessing system condition solely through periodic inspections, increasing attention is being paid to approaches based on monitoring data that enable early fault detection and predictive maintenance [1].

In recent years, digital twin technology has received considerable attention for monitoring the technical condition of photovoltaic systems, detecting faults, and forecasting their operational performance. A digital twin is a dynamic virtual representation of a physical object in a digital environment that can be used for condition monitoring, maintenance, and optimization of operating modes. Studies focusing on PV systems have identified the integration of digital twin technology with predictive maintenance, fault detection and diagnostics, the Internet of Things (IoT), and artificial intelligence (AI) as promising research directions [2].

However, the development of digital twins for photovoltaic systems has not yet reached full maturity. A systematic review of the literature on PV digital twins indicates that many existing studies do not adequately incorporate key characteristics of a fully developed digital twin, particularly bidirectional data exchange between the physical and virtual entities and the capability of the model to adapt itself to changing operating conditions. It has been reported that only 3.3% of the reviewed

studies satisfied all of the proposed criteria for PV digital twins [4].

The development of artificial intelligence-based predictive maintenance and fault diagnosis methods is advancing this field to a new stage of research. Modern approaches enable the joint analysis of sensor, historical, meteorological, and electrical measurement data, thereby providing opportunities for early fault detection, assessment of fault severity, and prediction of potentially critical future conditions [3].

Accordingly, the aim of this study is to develop the scientific and methodological foundations of an adaptive digital twin method for photovoltaic systems that dynamically represents the system condition through AI-based processing of real-time monitoring data, environmental conditions, electrical and energy-related parameters, and technical-operational characteristics, while enabling early fault detection and contributing to the reduction of energy losses.

2. Research methodology

The present study is conducted using an analytical-conceptual methodology. The research materials consist of scientific publications and methodological approaches addressing fault detection in photovoltaic (PV) systems, condition assessment, digital twin development, artificial intelligence-based diagnostics, and monitoring of energy production losses [1–7].

The methodological framework of the study is based on an adaptive digital twin architecture incorporating the principles of **physical photovoltaic system → monitoring data → virtual model → artificial intelligence → feedback**. Data acquired from the physical system are used to continuously update the state of the virtual model, while the virtual model establishes the expected normal operating conditions of the system.

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Deviations between the actual and predicted states are evaluated as potential indicators of faults [6].

For the purposes of the study, the collected data are classified into four principal groups:

- 1) Environmental parameters;
- 2) Electrical and energy-related parameters;
- 3) Technical condition parameters;
- 4) Time-series data.

At the initial stage of data processing, timestamp synchronization, identification of missing values, detection and separation of anomalous observations, and parameter normalization are performed [1,7].

The overall algorithmic sequence of the proposed method can be expressed as follows:

$$X(t) \rightarrow D(t) \rightarrow DT(t) \rightarrow \Delta(t) \rightarrow AI \rightarrow \hat{F}(t+\Delta t) \rightarrow \hat{L}E(t+\Delta t) \rightarrow Q. \quad (1)$$

Here, $X(t)$ denotes the initial multivariate data; $D(t)$ represents the processed data; $DT(t)$ denotes the digital twin; $\Delta(t)$ represents the deviation between the actual and virtual results; AI denotes the artificial intelligence-based analysis and forecasting module; $\hat{F}(t+\Delta t)$ represents the predicted probability of a potential fault condition; $\hat{L}E(t+\Delta t)$ denotes the predicted energy loss; and Q represents the technical decision.

General criterion for fault assessment:

$$\Delta P(t) = P_{DT}(t) - P_{real}(t) \quad (2)$$

The energy loss is defined as:

$$L_E = \int_{t_1}^{t_2} [PDT(t) - P_{real}(t)] dt \quad (3)$$

Here, L_E denotes the total energy loss; t_1 is the start time of the observation period; t_2 is the end time of the observation period; and dt represents an infinitesimal time interval.

For discrete monitoring data, the energy loss can be calculated as:

$$L_E \approx \sum_i [PDT(ti) - P_{real}(ti)] \Delta t \quad (4)$$

These expressions represent conceptual assessment formulas and will be calibrated in subsequent experimental studies using real monitoring data.

3. Results and Discussion

The analysis of the literature and existing methodological approaches indicates that research on fault detection in photovoltaic (PV) systems has primarily developed in the areas of monitoring, anomaly detection, fault diagnosis, and predictive maintenance [1–7]. The main outcome of the present study is the development of a concept that integrates these individual research directions into a unified adaptive digital twin architecture.

Table 1

Comparative analysis of existing approaches for photovoltaic systems

No.	Approach	Task	Advantage	Limitation	Proposed Solution
1	Monitoring and anomaly detection [1]	Detection of deviations	Real-time operational monitoring	Not fully integrated with forecasting	Deviations are transferred to the AI module
2	AI-based fault diagnosis [5]	Identification of fault types	Detects complex relationships	Dependent on data quality	AI is integrated into the adaptive DT module
3	Digital Twin-based diagnostics [6]	Comparison of physical and virtual states	Evaluates expected system conditions	Adaptability may be limited	The model is continuously updated using real-time data
4	Predictive maintenance [3]	Assessment of fault development	Enables preventive maintenance	Energy consequences are not always incorporated	Energy-loss forecasting is integrated
5	Adaptive Digital Twin	Comprehensive system management	Integrates monitoring, diagnostics, and forecasting	Requires real-world validation	Model proposed in this study

Source: compiled by the authors based on [1]–[6].

The operational logic of the proposed model is based on the following sequential workflow:

Physical PV system → real-time monitoring → data preprocessing → digital twin → comparison of actual and

virtual states → early anomaly detection → AI-based fault prediction → energy-loss assessment → technical decision.



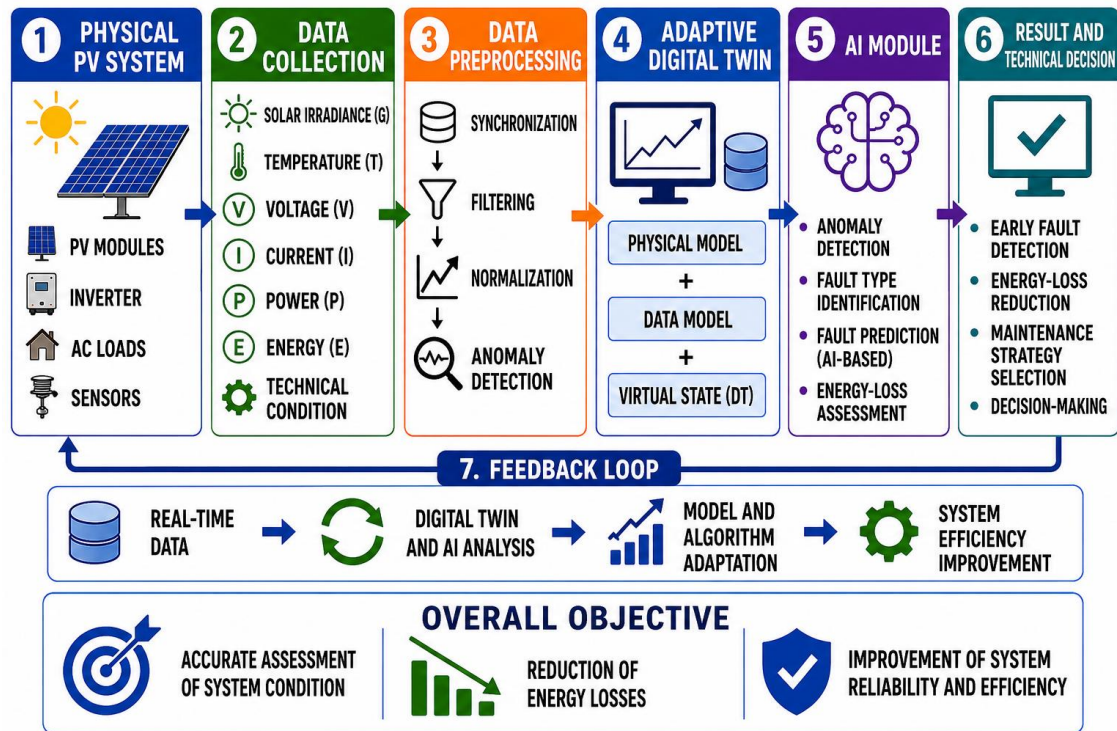


Fig. 1. Functional architecture of an artificial intelligence-based adaptive digital twin for photovoltaic systems

The central element of the proposed model is the **residual deviation indicator** between the physical system and its digital twin:

$$\varepsilon(t) = Y_{\text{real}}(t) - \hat{Y}_{\text{DT}}(t). \quad (5)$$

If the value of $\varepsilon(t)$ consistently exceeds the adaptive threshold, it is considered an early indication of a potential anomaly in the system. The threshold value is defined as an adaptive threshold that is dynamically updated according to solar irradiance, module temperature, ambient environmental

conditions, and operating modes. The scientific novelty of the study is reflected in the following aspects: the environmental, electrical-energy, and technical-operational parameters of the PV system are integrated into a unified multivariate information model; the digital twin is dynamically updated using real-time monitoring data; the residual deviation between the physical and virtual systems is analyzed using artificial intelligence; and the predicted fault is linked to its corresponding energy-related consequences.

Table 2

Functional stages of the proposed adaptive digital twin method

Stage	Input Data	Main Operation	Output
1. Monitoring	Irradiance, temperature, current, voltage, power	Real-time data acquisition	Initial data stream
2. Data Preprocessing	Initial data	Synchronization and quality control	Reliable data set
3. Digital Twin	Multivariate data	Normal operating condition modeling	Expected system state
4. Early Detection	Actual and virtual outputs	Residual deviation analysis	Anomaly signal
5. AI-Based Forecasting	Deviations and time-series data	Fault prediction	Probable future state
6. Energy Assessment	Fault prediction	Estimation of potential energy loss	Energy-loss forecast
7. Decision-Making	Diagnostics and forecast results	Selection of maintenance strategy	Preventive maintenance decision

Source: developed by the authors based on [1]–[7].



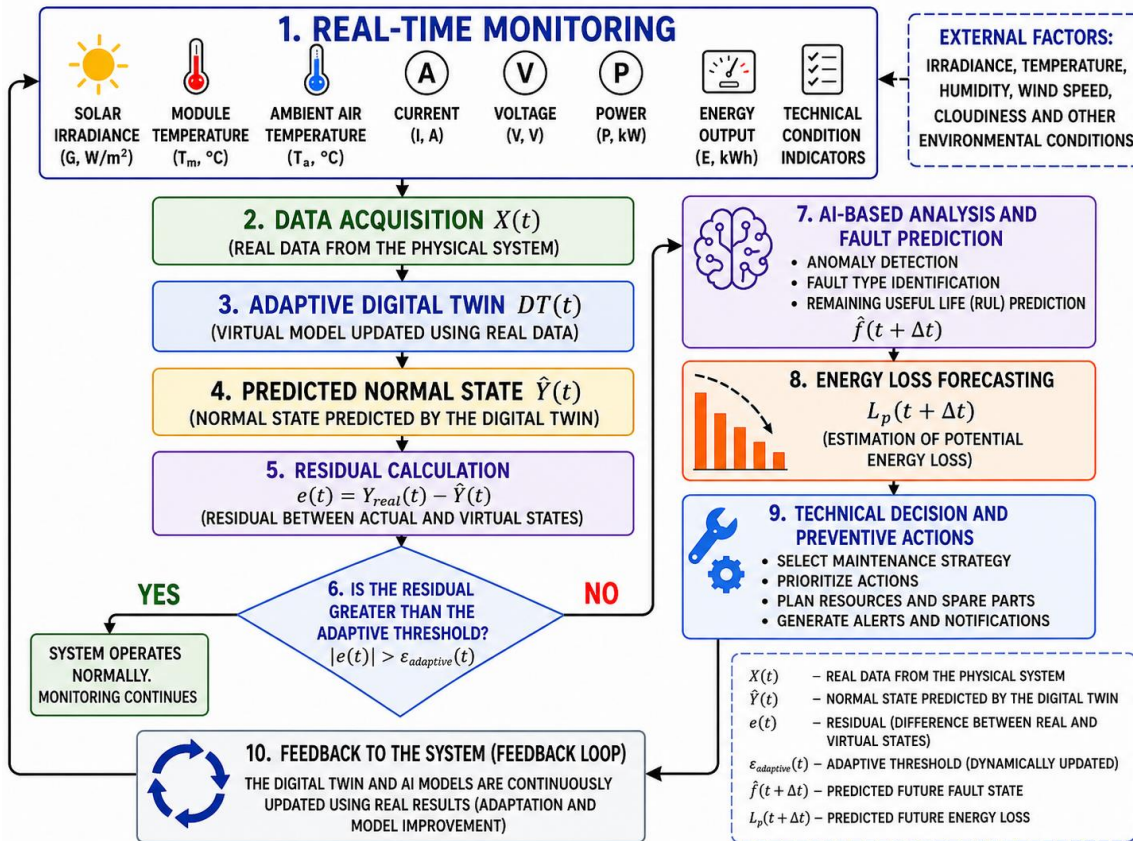


Fig. 2. Adaptive control cycle for early fault detection and energy-loss forecasting.

An important advantage of the proposed method is that the technical condition and energy performance are linked within a unified control cycle. Two anomalies of the same severity level may result in different amounts of energy loss under different operating conditions. Therefore, it is more appropriate to make technical decisions not solely on the basis of the presence of a fault, but also by considering its predicted energy-related consequences. In existing studies, AI-based predictive maintenance is regarded as a promising tool for optimizing maintenance strategies in PV systems [3,5]. In the proposed approach, predictive maintenance is integrated with the digital twin, forming the following decision-making chain: “condition assessment → cause evaluation → future-state forecasting → energy-loss estimation → decision-making.” Systematic analyses of PV Digital Twin technologies identify adaptability and bidirectional data exchange as important directions for further development [4]. From this perspective, the main methodological contribution of the present study is the integration of a dynamically updated virtual model, continuously calibrated using real-world operational data, with AI-based diagnostic and energy-loss forecasting modules within a unified framework.

The scientific hypothesis of the study is formulated as follows:

If the digital twin of a photovoltaic system is adaptively updated using real-world operational data, and deviations between the physical and virtual states are analyzed over time using artificial intelligence, then the capability to detect faults before they cause a significant increase in energy losses and to forecast their potential energy-related consequences can be substantially enhanced.

4. Techno-economic justification and research gaps

The integration of Digital Twin (DT) models to enhance the autonomous reliability of photovoltaic (PV) systems is justified based on economic and operational criteria [5]. Unlike conventional monitoring systems, an intelligent DT architecture with bidirectional communication can contribute to reducing the levelized cost of electricity (LCOE) [1]. An autonomous digital twin system can reduce the LCOE through two major pathways: increasing energy yield and reducing operating expenditures (OPEX) [3]. By enabling the early detection of anomalous conditions and short-circuit faults using artificial intelligence [2], the system can minimize plant downtime through autonomous switching and self-healing of affected circuits without direct human intervention. On the other hand, in desert and semi-desert regions, decisions regarding PV panel cleaning can be made based on economic criteria. If the value of the recovered energy exceeds the cost of cleaning and no rainfall is expected in the near future, the system can automatically initiate waterless robotic cleaning operations. This approach can substantially reduce logistical and labor costs under water-scarcity conditions, thereby shortening the payback period of capital expenditures (CAPEX).

4.1. Critical research gaps

An analysis of fundamental research and international trends in the field has identified the following three critical research gaps at both global and regional levels: Lack of bidirectional data flow and control (Bidirectional Control). Only 3.3% of global PV Digital Twin (PVDt) studies have implemented genuine bidirectional communication [1]. Most existing models remain at the Digital Shadow stage, in which data flow primarily from the physical PV plant to its



virtual representation, without enabling autonomous feedback or control commands to be transmitted back to the physical system. Insufficient modeling of regional climatic factors. Existing digital twin frameworks and advanced AI algorithms have predominantly been developed and evaluated under European or temperate climatic conditions [4]. Consequently, they do not adequately account for climate-specific factors characteristic of Uzbekistan, particularly the Kyzylkum Desert and Aral Sea regions, such as the accumulation rate of saline dust, dust cementation phenomena, and long-term experimental measurements obtained from PV installations operating under comparable local environmental conditions. Limitations of hybrid modeling approaches. To reliably distinguish extreme climatic anomalies from physical system faults, there is a need for the parallel evaluation and integration of purely data-driven models with physics-based mathematical models. However, methodologies for developing such integrated, multi-domain hybrid architectures capable of combining physical knowledge with data-driven intelligence have not yet been sufficiently developed [1,5].

4. Conclusion

This study developed the scientific and methodological foundations of an artificial intelligence-based adaptive digital twin method aimed at the early detection of faults occurring in photovoltaic (PV) systems and the reduction of associated energy losses. Within the framework of the study, a functional architecture was proposed comprising the physical PV system, real-time monitoring, data preprocessing, an adaptive digital twin, comparison of actual and virtual states, AI-based fault prediction, and energy-loss assessment. The scientific novelty of the proposed approach lies in evaluating the residual deviation between the physical system and its virtual model using adaptive thresholds, integrating the processes from monitoring to technical decision-making within a unified architecture, and linking predicted fault conditions to their potential energy-loss consequences. The proposed approach provides a methodological basis for transitioning from periodic diagnostics to condition-based and predictive maintenance management. At the same time, the study is analytical and conceptual in nature; therefore, the quantitative performance of the proposed model should be experimentally validated at the next stage using long-term monitoring data from real photovoltaic power plants.

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O. Khamidov, Sh. Samatov, B. Gayratov, A. Djuraev

Improving the reliability of the TD802 direct-current traction generator of the ChME3 shunting diesel locomotive through insulation replacement.....118

U. Turdialiev, D. Boykishieva

Assessing the impact of integrating lean manufacturing methods into the quality management system on the efficiency of a mechanical engineering enterprise.....125

B. Sobirov, N. Botirova

Use of mineral fillers for PVC-based linoleum production and investigation of their physical and mechanical properties.....130

G. Uzakov, M. Majidova

Development of an artificial intelligence-based adaptive digital twin method for early fault detection and energy loss reduction in solar photovoltaic systems.....133

U. Khamrokulov

Precast-monolithic frame building system based on permanent reinforced concrete shell formwork: Analysis of world practice and experimental substantiation.....138

Z. Kurbonov, S. Bozorboev

Mechanically induced surface modification of diabase aggregate for high-performance concrete.....144