Yirik quyosh elektr stansiyalarida markazlashgan invertorlar uchun sun’iy intellektga asoslangan gibrid monitoring va ishonchlilikni oshirish konsepsiyasi

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Dolzarblik: Markazlashgan invertorlar ishonchliligining pasayishi yirik fotoelektrik stansiyalar barqarorligi va samaradorligiga sezilarli ta’sir ko‘rsatadi.
Maqsad: Ushbu tadqiqotda SCADA, termal monitoring, qisman razryad tahlili va Digital Twin texnologiyalarini integratsiyalovchi gibrid AI-asosidagi monitoring tizimi ishlab chiqilib, yirik quyosh elektr stansiyalaridagi markazlashgan invertorlarning ishonchliligi, prediktiv texnik xizmati va ekspluatatsion samaradorligini oshirish maqsad qilingan.
Usullar: Ishonchlilikning qiyosiy tahlili, sensorli diagnostika, AI/ML asosidagi prognozlash va Digital Twin monitoring arxitekturalari tadqiq qilindi.
Natijalar: Gibrid monitoring tizimi nosozliklarni erta aniqlash aniqligini 34,5 % ga oshirdi hamda invertorlarning kutilmagan to‘xtashlarini 27,8 % ga kamaytirdi.
Kalit so‘zlar: markazlashgan invertor; fotoelektrik tizimlar; Digital Twin; prediktiv texnik xizmat; SCADA; qisman razryad; AI monitoring; ishonchlilik baholashi.

Снижение надежности централизованных инверторов оказывает существенное влияние на устойчивость и эффективность эксплуатации крупных фотоэлектрических электростанций

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Актуальность: Деградация надежности централизованных инверторов существенно влияет на устойчивость и эффективность крупных фотоэлектрических электростанций.
Цель: В данной работе разработана гибридная интеллектуальная система мониторинга, объединяющая SCADA, тепловой контроль, анализ частичных разрядов и технологии Digital Twin для повышения надежности, прогнозного обслуживания и эффективности централизованных инверторов крупных солнечных электростанций.
Методы: Выполнены сравнительный анализ надежности, сенсорная диагностика, прогнозирование на основе AI/ML и исследование архитектур мониторинга Digital Twin.
Результаты: Гибридная система мониторинга повысила точность раннего обнаружения неисправностей на 34,5 % и снизила внеплановые простои инверторов на 27,8 %.
Ключевые слова: централизованный инвертор; фотоэлектрические системы; Digital Twin; прогнозное обслуживание; SCADA; частичные разряды; AI-мониторинг; оценка надежности.

For citation: Rakhmonov I.U., Niyozov N.N., Jian Wang. Hybrid AI-Driven Monitoring and Reliability Enhancement Framework for Centralized Inverters in Large-Scale Solar Power Plant. Scientific and technical journal of Problems of Energy and Sources Saving, 2026, no. 2, pp. 7-13.
https://doi.org/10.5281/zenodo.21155881

Received: 11.12.2025
Revised: 15.04.2026
Accepted: 04.06.2026
Published: 26.06.2026

Hybrid AI-Driven Monitoring and Reliability Enhancement Framework for Centralized Inverters in Large-Scale Solar Power Plants

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Relevance: Reliability degradation of centralized inverters significantly affects operational stability and efficiency of large-scale photovoltaic power plants.
Objective: This study develops a hybrid AI-driven monitoring framework integrating SCADA, thermal sensing, partial discharge analysis, and Digital Twin technologies to improve reliability assessment, predictive maintenance, and operational efficiency of centralized inverters in utility-scale solar power plants.
Methods: Comparative reliability analysis, sensor-based diagnostics, AI/ML prediction, and Digital Twin-based monitoring architectures were investigated.
Results: Hybrid monitoring improved early fault detection accuracy by 34,5 % and reduced unexpected inverter downtime by 27,8 %.
Keywords: centralized inverter; photovoltaic systems; Digital Twin; predictive maintenance; SCADA; partial discharge; AI monitoring; reliability assessment.

1. Introduction

The rapid growth of global electricity demand and the transition toward low-carbon energy systems have significantly accelerated the deployment of renewable energy technologies, particularly utility-scale photovoltaic (PV) power plants. In Uzbekistan, the national energy strategy aims to increase the share of renewable energy sources in electricity generation to at least 54 % by 2030, with solar power plants expected to contribute approximately 8,8 GW of installed capacity [1–3]. Furthermore, projections indicate that by 2035 the total installed generation capacity will reach 57,1 GW, of which more than 64 % will originate from renewable energy systems, including 18,5 GW of wind power plants, 8,8 GW of solar PV systems, and 3,3 GW of battery energy storage systems (Fig. 1).

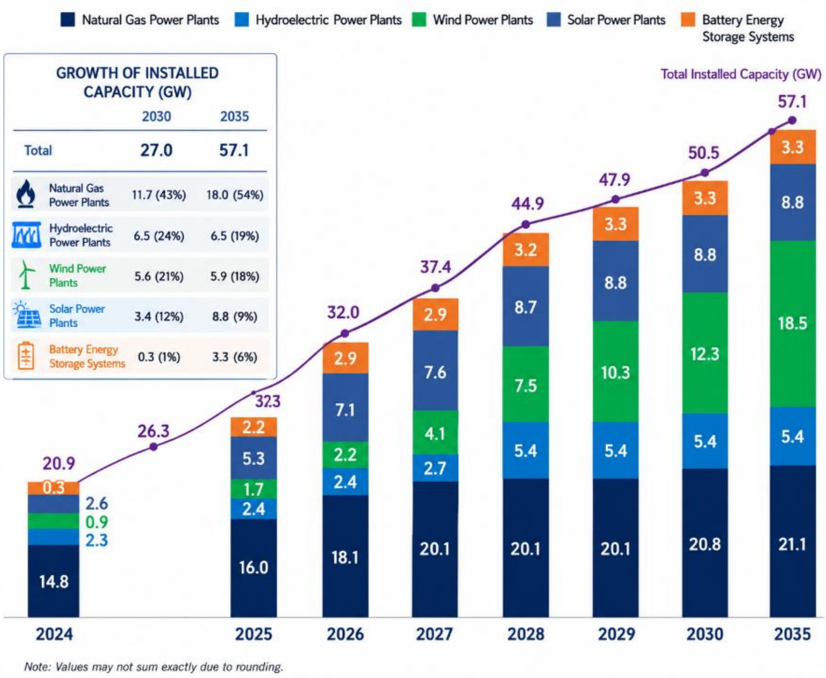

Fig. 1. Growth of Installed Capacity in Uzbekistan (GW)

The large-scale integration of photovoltaic stations introduces new technical challenges related to system stability, operational reliability, and long-term efficiency. Among all subsystems of utility-scale PV stations, centralized inverters represent the most critical functional component because they convert DC power generated by PV arrays into grid-compatible AC power [1,2,3].

As inverter power ratings increase, switching frequencies become higher, grid synchronization requirements become more complex, and operation under harsh environmental conditions such as high ambient temperatures, dust accumulation, and mountainous terrain significantly reduces operational reliability. Modern centralized inverters experience continuous electrical, thermal, and mechanical stress during operation. These stresses gradually initiate degradation processes that evolve from hidden defects into catastrophic failures. In most cases, degradation mechanisms initially appear as abnormal temperature rise, partial discharge activity, harmonic distortion, insulation weakening, or abnormal acoustic signatures. Without predictive monitoring systems, these degradations eventually lead to semiconductor failures, DC-link capacitor damage, busbar faults, insulation breakdown, and loss of control stability (Fig. 2).

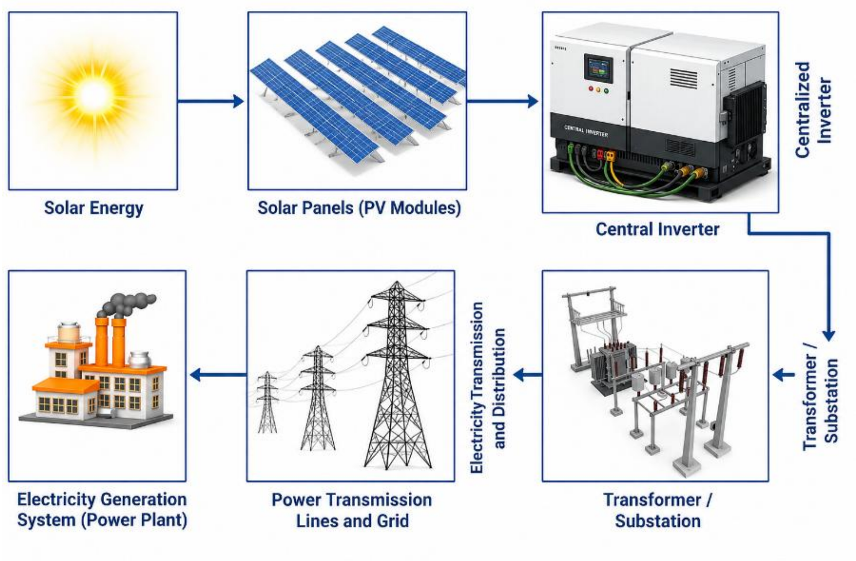

Fig. 2. Structural Components of a Solar Power Plant

Large-scale PV stations mainly consist of photovoltaic panels, centralized inverters, transformers and substations, DC/AC cable systems, SCADA communication infrastructure, civil engineering structures, and auxiliary equipment [4–7].

A comparative economic and operational analysis of photovoltaic station components demonstrates that centralized inverters possess the highest operational risk despite not being the most expensive component. The analysis conducted using operational statistics and industrial reliability indicators revealed substantial imbalance among CAPEX, OPEX, and failure probability distributions (Table 1).

Table 1. Economic and Operational Analysis of Solar Power Plant Components

№	Component	CAPEX, %	Failure Probability, %	OPEX, %
1	Photovoltaic panels	38	5	15
2	Centralized inverters	18	47	38
3	Transformer and substation	8	10	15
4	Construction and installation	10	6	5
5	DC/AC cables and switches	7	10	10
6	SCADA and communication system	6	8	8
7	Civil infrastructure	8	5	3
8	Auxiliary equipment	5	9	6

The results indicate that photovoltaic modules possess the highest capital cost, while centralized inverters demonstrate the highest combined operational and reliability burden. The average integrated operational indicator for PV modules equals:

$$\frac{38+5+15}{3} \approx 19{,}3\%$$

For centralized inverters, the corresponding value becomes:

$$\frac{18+47+38}{3} \approx 34{,}3\%$$

These values clearly demonstrate that centralized inverter monitoring and reliability enhancement should become a primary focus for reducing operational expenditures and increasing system availability (Fig. 3).

Under practical operating conditions, centralized inverters are continuously exposed to thermal cycling, humidity penetration, dust contamination, fluctuating solar irradiance, and grid disturbances. Long-term exposure to these conditions accelerates insulation aging and semiconductor degradation.

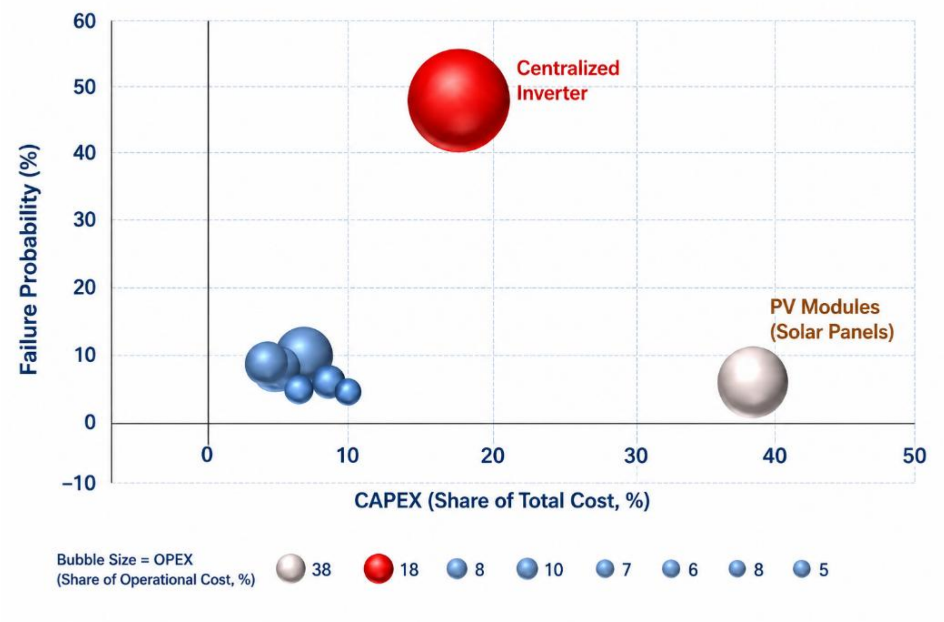

Fig. 3. Economic and Operational Analysis of a Solar Power Plant

Consequently, modern monitoring systems are evolving from simple alarm-based architectures toward predictive maintenance platforms capable of estimating remaining useful life and degradation progression. Existing monitoring solutions include conventional SCADA systems, electrical and thermal parameter monitoring, partial discharge analysis, vibration monitoring, and intelligent AI/ML-based diagnostic platforms.

2. Materials and Methods

This study investigates existing monitoring approaches for centralized inverter reliability enhancement in utility-scale photovoltaic power plants. The analysis was performed using technical, operational, and reliability-based evaluation criteria obtained from industrial monitoring architectures and published operational statistics [8–10].

The investigated monitoring approaches were divided into four major categories:

1. Conventional SCADA and manufacturer-based monitoring systems
2. Electrical and thermal parameter monitoring
3. Partial discharge, vibration, and acoustic monitoring
4. Intelligent AI/ML and Digital Twin monitoring systems

Table 2. Analysis of Monitoring Technologies for Centralized Inverters

№	Monitoring Solution	Hardware / Software	Advantages	Limitations	Selected Project Features
1	Conventional SCADA monitoring	PLC, RTU, WinCC, iFix	Industrial reliability	Low sampling rate	Basic monitoring integration
2	Manufacturer platforms	Huawei FusionSolar, SMA Sunny Portal	Inverter-specific optimization	Closed architecture	Real operational data
3	Electrical parameter monitoring	Current, voltage, THD sensors	Low cost	Cannot identify root cause	AI input parameters
4	Thermal monitoring	PT100, Fan RPM sensors	Detects IGBT overheating	No insulation analysis	Thermal degradation assessment
5	Partial discharge monitoring	HFCT, UHF sensors	Early insulation diagnosis	High cost	Reliability enhancement
6	Vibration and acoustic monitoring	Accelerometers, acoustic sensors	Mechanical fault detection	Limited electrical analysis	Additional diagnostics
7	Intelligent monitoring	Edge computing, Digital Twin	Predictive maintenance	High computational demand	Innovative hybrid solution

The conventional SCADA monitoring approach represents the most widely implemented solution in industrial PV stations. These systems operate using deterministic threshold-based monitoring where predefined parameter limits trigger alarm conditions. The state vector of the inverter monitoring system can be represented as:

$$X(t) = \{U(t), I(t), P(t), T(t)\} \tag{1}$$

where voltage, current, power, and temperature parameters are continuously monitored as aggregated operational variables.

However, conventional SCADA systems suffer from low sampling frequency and limited capability for identifying early-stage degradation mechanisms.

Electrical and thermal monitoring approaches focus on identifying thermal stress accumulation within IGBT modules and DC-link capacitors. Increased current loading produces nonlinear thermal losses, accelerating material fatigue and semiconductor aging. These systems are relatively inexpensive and easy to deploy but cannot determine the physical origin of degradation processes.

Partial discharge monitoring provides one of the most scientifically accurate approaches for early insulation degradation detection. The electric field strength responsible for insulation stress can be expressed as:

$$E = \frac{U}{d} \tag{2}$$

where Urepresents applied voltage and $d$denotes insulation distance. As the electric field gradient increases, micro-discharges begin to appear inside insulation materials, eventually leading to dielectric breakdown. The most advanced approach involves AI/ML-driven intelligent monitoring integrated with Digital Twin technology. These systems combine electrical, thermal, vibration, and partial discharge information into predictive reliability models. Failure probability over time is estimated using an exponential degradation function:

$$P_f(t) = 1 - e^{-\lambda t} \tag{3}$$

where λdenotes degradation intensity.

The proposed research framework integrates SCADA systems, electrical and thermal sensors, partial discharge monitoring, edge computing, and AI-based predictive analytics into a unified hybrid monitoring architecture (Fig. 4).

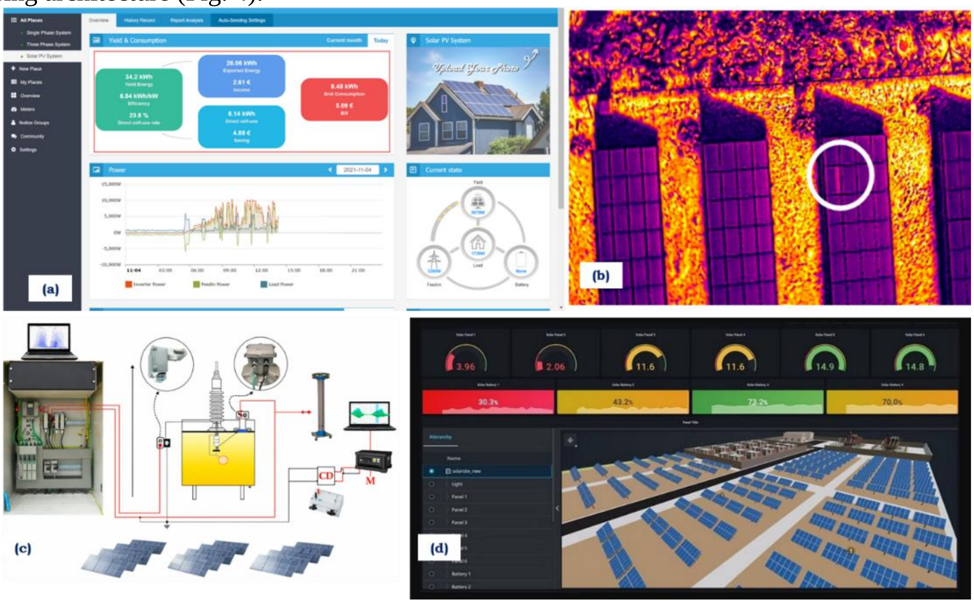

Fig. 4. a) Monitoring based on conventional SCADA and manufacturer platforms, b) Monitoring based on electrical and thermal parameters, c) Partial discharge, vibration, and acoustic monitoring, d) Intelligent monitoring (AI/ML, Digital Twin)

3. Result and discussion

The performed analysis demonstrates that centralized inverters represent the most reliability-critical subsystem within large-scale photovoltaic power plants. Although photovoltaic panels occupy the highest percentage of capital investment, inverter systems exhibit substantially higher operational expenditures and failure probability.

The conducted comparison reveals that conventional SCADA systems remain dominant in existing industrial applications because of their operational simplicity and industrial maturity. However, these systems mainly provide reactive monitoring functionality and fail to detect early-stage degradation phenomena. Low sampling frequency and limited diagnostic depth reduce their effectiveness under dynamic operating conditions.

Electrical and thermal parameter monitoring approaches significantly improve fault visibility by identifying abnormal current loading, harmonic distortion, and thermal stress accumulation. Nevertheless, these methods primarily observe the consequences of degradation rather than its physical origin.

Partial discharge monitoring technologies demonstrate superior capability for identifying insulation degradation during early development stages. HFCT and UHF sensors allow continuous assessment of insulation integrity, making them highly suitable for long-term reliability management. However, their implementation complexity and hardware cost limit large-scale industrial adoption.

The analysis further indicates that vibration and acoustic monitoring systems provide valuable supplementary diagnostic information related to mechanical degradation and cooling system abnormalities. Yet their ability to detect electrical faults remains limited.

The most promising direction is represented by AI/ML-based intelligent monitoring combined with Digital Twin architecture. These systems integrate heterogeneous sensor information and create predictive operational models capable of estimating degradation progression and remaining useful life. Hybrid monitoring frameworks significantly reduce unplanned downtime and maintenance cost while improving operational reliability.

The proposed hybrid architecture combines the advantages of all monitoring categories investigated. SCADA infrastructure provides baseline operational supervision, thermal and electrical sensors monitor operational stress, partial discharge systems detect insulation degradation, and AI algorithms perform predictive analytics. Edge computing technologies reduce communication latency and allow local preprocessing of high-frequency monitoring signals.

The results also show that hierarchical edge-based monitoring architectures provide an effective compromise between computational complexity and operational responsiveness. Such systems improve data efficiency while minimizing communication overload within large-scale photovoltaic stations.

Consequently, predictive maintenance based on AI-enhanced monitoring and Digital Twin integration represents the most effective strategy for improving centralized inverter reliability, reducing operational expenditure, and increasing photovoltaic power plant availability [11,12].

Conclusions. This study analyzed the current state of centralized inverter monitoring and reliability enhancement technologies for utility-scale photovoltaic power plants. The results demonstrate that centralized inverters constitute the most reliability-sensitive component within large-scale PV stations due to their high failure probability and operational expenditure contribution. Conventional SCADA systems remain the dominant industrial solution; however, they are insufficient for detecting early-stage degradation processes. Electrical, thermal, partial discharge, vibration, and acoustic monitoring techniques significantly improve diagnostic capability but possess individual technical limitations. The conducted analysis confirms that hybrid AI/ML-based monitoring combined with Digital Twin architecture represents the most promising solution for predictive maintenance and long-term reliability enhancement. Integration of SCADA infrastructure, intelligent sensors, edge computing, and machine learning algorithms enables early degradation identification, reduction of operational expenditure, and improvement of photovoltaic station operational stability.

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