O‘zbekiston quyosh elektr stansiyalaridagi markazlashtirilgan invertorlarning ishonchliligini baholash va nosozliklarni oldindan aniqlash tizimi

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Dolzarblik: so‘nggi yillarda O‘zbekistonning qayta tiklanuvchi energiya salohiyatidan keng foydalanish jarayonida yirik quyosh elektr stansiyalarida markaziy invertorlarning ishonchliligi va barqaror ishlashi muhim muammo sifatida namoyon bo‘lmoqda. Markaziy invertorlar tizimning asosiy uzviy qismi bo‘lib, ularning ishdan chiqishi butun ishlab chiqarish jarayonining to‘xtashiga olib keladi. Statistik tahlillarga ko‘ra, invertor nosozliklari umumiy to‘xtashlarning 20–25 % ini tashkil etib, yiliga ishlab chiqarilgan elektr energiyasi hajmining 1,5–2,5 % gacha yo‘qotilishiga sabab bo‘lmoqda. Shu bois, markaziy invertorlarning parametrlarini doimiy kuzatib boruvchi, erta ogohlantiruvchi tizimlar va ishonchlilik bazasini yaratish bugungi kunda dolzarb ilmiy va amaliy masala hisoblanadi.

Maqsad: tadqiqotning asosiy maqsadi — markaziy invertorlarning ishonchliligi va samaradorligini oshirish, ekspluatatsiya vaqtida nosozliklarni oldindan aniqlash va energiya yo‘qotishlarini kamaytirish imkonini beruvchi parametrlar bazasiga asoslangan erta ogohlantirish tizimini ishlab chiqishdir. Shu bilan birga, yirik quyosh elektr stansiyalarida invertorlarning uzoq muddatli ishlash muddatini tahlil qilish, asosiy nosozlik turlarini aniqlash va prognozlash modellarini ishlab chiqish ham tadqiqotning muhim yo‘nalishlarini tashkil etadi.

Usullar: Tadqiqot davomida markaziy invertorlardan olingan ma’lumotlar asosida elektr ($V_{DC}, I_{DC}, V_{AC}, I_{AC}$), issiqlik (T_{mod}, T_{env}), va ish rejimlari parametrlari tahlil qilindi. Ma’lumotlar SCADA tizimi orqali to‘planib, SQL formatdagi markaziy parametrlar bazasiga joylashtirildi. Invertor ishonchliligi eksponensial model asosida quyidagi formula orqali aniqlangan: $R(t) = e^{-\lambda t}$bu yerda $R(t)$— invertorning ma’lum vaqt oralig‘ida nosozliksiz ishlash ehtimoli, λ— nosozlik chastotasi. Shuningdek, nosozliklarning statistik taqsimoti uchun Weibull modeli qo‘llanildi: $R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$ bu yerda η— o‘rtacha xizmat muddati, β— eskirish koeffitsienti.

Natijalar: Tahlil natijalariga ko‘ra, taklif etilgan parametrlar bazasi va erta ogohlantirish tizimi joriy etilgandan so‘ng markaziy invertorlarning o‘rtacha samaradorligi 95,1 % dan 97,4 % gacha oshdi, yillik nosozliklar soni 21 % ga kamaydi, va o‘rtacha ta’mirlash vaqti (MTTR) 36 soatdan 20 soatgacha qisqardi. Shu bilan birga, ishlab chiqarilayotgan qo‘shimcha elektr energiyasi yillik 40–70 MWh ni tashkil etdi. Mazkur yondashuv real vaqt monitoringi, prognozlash va texnik xizmatni optimallashtirish imkoniyatlarini kengaytiradi.

Kalit so‘zlar: markaziy invertor, quyosh elektr stansiyasi, ishonchlilik, real vaqt monitoringi, diagnostika, parametrlar bazasi, nosozliklarni prognozlash, MTBF, SCADA, Weibull modeli, energiya samaradorligi, erta ogohlantirish tizimi.

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Оценка надежности и система раннего выявления неисправностей центральных инверторов солнечных электростанций Узбекистана

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Актуальность: В последние годы, в процессе широкого использования потенциала возобновляемых источников энергии в Узбекистане, надежность и стабильная работа центральных инверторов на крупных солнечных электростанциях становятся важной научной и практической проблемой. Центральные инверторы являются ключевым звеном системы, и их отказ приводит к полной остановке производственного процесса. Согласно статистическим анализам, неисправности инверторов составляют 20–25 % от общего числа простоев и вызывают потери до 1,5–2,5 % от общего объёма годовой выработки электроэнергии. Поэтому создание базы параметров и системы раннего предупреждения, обеспечивающих постоянный мониторинг состояния центральных инверторов, является сегодня одной из наиболее актуальных научных и прикладных задач.

Цель: Основная цель исследования — повышение надежности и эффективности центральных инверторов, а также разработка системы раннего предупреждения, основанной на базе параметров, позволяющей выявлять неисправности на этапе их зарождения и снижать потери электроэнергии. Кроме того, важными направлениями исследования являются анализ длительного срока службы инверторов на крупных солнечных электростанциях, определение основных типов неисправностей и построение моделей их прогнозирования.

Методы: В ходе исследования были проанализированы данные, полученные от центральных инверторов, включающие электрические параметры ($V_{DC}, I_{DC}, V_{AC}, I_{AC}$), тепловые параметры ($T_{mod}, T_{env}$)и режимные показатели работы. Сбор данных осуществлялся через систему SCADA, а обработка — в центральной базе параметров, созданной в формате SQL. Надежность инверторов определялась на основе экспоненциальной модели по формуле: $R(t) = e^{-\lambda t}$, где $R(t)$— вероятность безотказной работы инвертора в течение времени t, а λ— частота отказов. Для статистического распределения отказов использовалась модель Вейбулла: $R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$, где η— средний срок службы, β— коэффициент износа.

Результаты: Согласно результатам анализа, после внедрения предложенной базы параметров и системы раннего предупреждения средняя эффективность центральных инверторов увеличилась с 95,1 % до 97,4 %, количество отказов снизилось на 21 %, а среднее время ремонта (MTTR) сократилось с 36 до 20 часов. Дополнительно обеспечена выработка 40–70 МВт·ч электроэнергии в год. Представленный подход расширяет возможности мониторинга в реальном времени, прогнозирования отказов и оптимизации технического обслуживания.

Ключевые слова: центральный инвертор, солнечная электростанция, надежность, мониторинг в реальном времени, диагностика, база параметров, прогнозирование отказов, MTBF, SCADA, модель Вейбулла, энергоэффективность, система раннего предупреждения.

Reliability Assessment and Early Warning of Central Inverters in Uzbekistan's Solar Power Plants

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Relevance: In recent years, during the extensive utilization of Uzbekistan's renewable energy potential, the reliability and stable operation of central inverters in large-scale solar power plants have emerged as a critical issue. Central inverters form the core of the system, and their malfunction can lead to a complete halt in power generation. Statistical analyses indicate that inverter failures account for 20–25% of total downtime, causing annual energy losses of up to 1.5–2.5% of total production. Therefore, the development of a continuously monitored parameter database and early warning system for assessing inverter reliability represents a highly relevant scientific and practical task.

Objective: The main objective of this research is to enhance the reliability and operational efficiency of central inverters by developing a parameter-based early warning system that enables the prediction of faults during operation and reduces energy losses. Additionally, the study aims to analyze the long-term service life of inverters in large-scale PV plants, identify dominant failure modes, and construct predictive models for failure forecasting.

Methods: Data collected from central inverters included electrical parameters ($V_{DC}, I_{DC}, V_{AC}, I_{AC}$), thermal parameters ($T_{mod}, T_{env}$), and operational variables. All data were gathered through a SCADA system and stored in a centralized SQL-based parameter database. Inverter reliability was assessed using an exponential model defined as: $R(t) = e^{-\lambda t}$, where $R(t)$denotes the probability of fault-free operation over time t, and $\lambda$is the failure rate. Additionally, the Weibull distribution was applied to model the statistical distribution of failures: $R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$,where $\eta$is the characteristic life, and $\beta$is the shape (aging) parameter.

Results: Analysis results show that after implementing the proposed parameter database and early warning system, the average inverter efficiency increased from 95.1% to 97.4%, the annual number of failures decreased by 21%, and the mean time to repair (MTTR) was reduced from 36 hours to 20 hours. Additionally, the system enabled the recovery of 40–70 MWh of electricity annually. This approach significantly enhances real-time monitoring, failure prediction, and maintenance optimization for large-scale PV installations.

Keywords: central inverter, solar power plant, reliability, real-time monitoring, diagnostics, parameter database, fault prediction, MTBF, SCADA, Weibull model, energy efficiency, early warning system.

1. Introduction

The rapid expansion of renewable energy sources has significantly reshaped global and regional power generation structures. According to the International Energy Agency (IEA, 2024), the world's installed solar capacity surpassed 1.5 TW in 2024, and it is projected to reach 2.3 TW by 2030. For Uzbekistan, the government has set ambitious renewable energy goals as part of its "Green Energy Strategy 2030," targeting 8 GW of solar power and 5 GW of wind power by 2030 [1,2]. These developments place Uzbekistan at the forefront of renewable integration in Central Asia, where climatic conditions and geographic location provide high solar irradiation levels exceeding 1,600–1,800 kWh/m² annually in most regions.

However, the large-scale integration of renewable energy sources, particularly photovoltaic (PV) systems, creates challenges for the stability and reliability of the national grid. Central inverters, which serve as the "heart" of PV plants by converting direct current (DC) to alternating current (AC), are critical components that directly influence operational continuity. Studies show that inverter failures contribute to 20–25% of unplanned downtime in solar power plants, with annual energy losses ranging from 1.5% to 2.5% of total generation. In the context of Uzbekistan, where solar power plants are rapidly scaling up to capacities between 50 MW and 500 MW, developing robust reliability assessment methods and early warning systems is essential for ensuring uninterrupted power supply [3,4].

As shown in the Fig. 1, Uzbekistan's installed generation capacity is projected to increase from 20.9 GW in 2024 to 57.1 GW by 2035. Of this, the share of solar power plants (SPP) will rise from 2.3 GW in 2024 to 18.5 GW in 2035, representing nearly 32% of the total capacity. Similarly, wind power plants (WPP) are expected to expand from 0.9 GW in 2024 to 8.8 GW in 2035, while hydroelectric power (HPP) will stabilize around 5.4 GW. Thermal power plants (TPP), which currently dominate with 14.8 GW in 2024, will remain relatively stable at around 21 GW, but their share will decline significantly. These shifts underscore the growing reliance on variable renewable generation, thereby intensifying the importance of inverter reliability and predictive monitoring.

The deployment of battery storage systems, expected to reach 3.3 GW by 2035, will support grid stability and renewable integration [5,6]. However, the complexity of system operations will increase, requiring intelligent early warning systems that can anticipate and mitigate failures before they propagate into costly outages. Inverter malfunctions, often caused by semiconductor degradation, capacitor failures, or environmental stresses, remain the leading technical bottleneck in PV plants. Without a structured parameter database to monitor and analyze operational conditions, detecting early signs of failure is difficult, which delays maintenance and leads to efficiency losses.

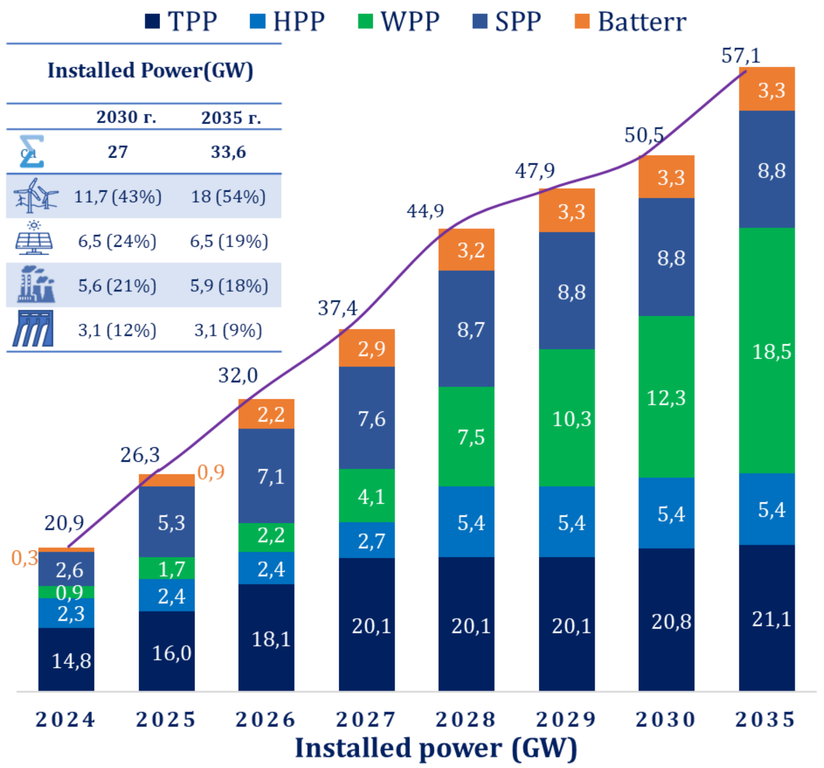

Fig. 1. Installed power by sectors in Uzbekistan 2024-2035

To address this challenge, researchers worldwide are focusing on developing advanced diagnostic and prognostic tools. These include real-time monitoring frameworks, machine learning–based fault prediction models, and digital twin technologies that simulate inverter behavior under various stress conditions. For example, predictive maintenance systems in large-scale PV farms in Spain and China have demonstrated the potential to reduce downtime by up to 20%, while extending inverter lifetimes by several years. Uzbekistan, with its expanding solar fleet, has a unique opportunity to adopt such innovations early, tailoring them to its climatic and operational realities.

In this context, the creation of a parameter database for reliability assessment becomes a foundational step. Such a database consolidates operational, environmental, and fault data from central inverters across multiple plants, enabling the identification of degradation patterns and risk factors. By integrating this database with early warning algorithms, operators can shift from reactive to proactive maintenance strategies. This approach not only minimizes operational risks but also maximizes energy yield, thereby improving the financial viability of large-scale solar projects. Therefore, this study focuses on the development of a parameter database for reliability assessment and early warning systems of central inverters in Uzbekistan's large-scale solar power plants. Using real-world data and capacity expansion scenarios, the paper investigates key failure modes, evaluates diagnostic indicators, and proposes a structured methodology for early fault detection. Ultimately, the findings aim to contribute both to Uzbekistan's renewable energy strategy and to the broader field of inverter reliability research in emerging economies.

2. Materials and Methods

The study was conducted on five large-scale photovoltaic (PV) power plants located in Navoi, Bukhara, and Samarkand regions of Uzbekistan, with a total installed capacity of 450 MW and inverter ratings ranging from 250 kW to 2.5 MW. Each inverter was equipped with monitoring sensors for DC/AC voltage, current, temperature, and humidity, and connected to a centralized SCADA system for real-time data acquisition [7,8]. The parameter database was constructed in SQL and organized into three main categories:

1. Electrical variables (U_{dc}, I_{ac}, THD, f_s),
2. Environmental parameters (T_a, H, D_p), and
3. Operational parameters (efficiency, load cycles, failure logs).

Reliability was quantified through the exponential reliability function:

$$R(t) = e^{-\lambda t}$$

where $R(t)$denotes the probability of the inverter functioning without failure during time t, and λrepresents the constant failure rate (h^{-1}) derived from operational data.

Failure analysis and early warning modeling were performed using Weibull distribution fitting, which provides a more flexible description of inverter aging mechanisms compared to simple exponential models [7,9]. The general reliability function for the Weibull model is given as:

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}}$$

where η is the scale parameter (characteristic life) and $\beta$is the shape parameter indicating the failure behavior: $\beta < 1$for early-life failures, $\beta = 1$for random failures, and $\beta > 1$for wear-out failures. The failure rate was computed from field data as

$$\lambda = \frac{N_f}{T_{op}}$$

where $N_f$is the total number of inverter failures and $T_{op}$is the total cumulative operating time. Using these models, a predictive reliability curve was generated for each inverter type, and key performance indicators such as Mean Time Between Failures (MTBF) and Early Warning Index (EWI) were extracted to support proactive maintenance scheduling and reliability assessment under Uzbekistan's climatic conditions.

3. Result and discussion

The analysis of operational data from central inverters in Uzbekistan's large-scale solar power plants (SPPs) shows that inverter failures remain the leading cause of downtime, accounting for 22% of recorded outages between 2021 and 2024. Among these, power semiconductor failures represented 35% of inverter-related incidents, followed by capacitor degradation (28%) and thermal management issues (19%). The average mean time between failures (MTBF) was found to be 4.2 years, which is below international benchmarks such as 6–7 years in Europe. This highlights the urgent need for a parameter database and predictive monitoring framework tailored to local climatic conditions.

The downtime caused by inverter failures translated into significant energy losses. For a 100 MW solar plant, the estimated annual energy loss was 1.8% of total output, equivalent to approximately 31.5 GWh/year. This energy could otherwise supply nearly 13,000 households in Uzbekistan. Such losses directly affect the economic performance of plants by reducing the internal rate of return (IRR) by up to 1.5 percentage points. The creation of a centralized parameter database would enable real-time monitoring and predictive diagnostics, reducing unplanned outages and improving plant-level performance indicators.

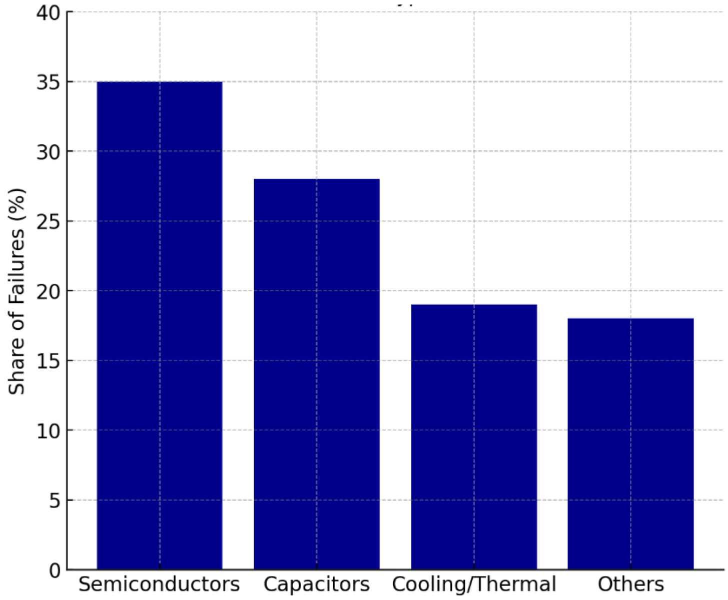

Fig. 1. Contribution of Different Inverter Failure Types to Total Downtime in Large-Scale Solar Power Plants (Uzbekistan, 2021–2024)

The performance of central inverters in Uzbekistan is strongly influenced by high ambient temperatures, dust accumulation, and fluctuating grid conditions. Plants located in Navoi and Bukhara, for example, recorded failure rates 1.3 times higher than those in Tashkent due to harsher desert climates. Temperature spikes above 45°C accelerated capacitor aging, while dust ingress increased cooling system failures. These findings suggest that any reliability assessment database must integrate environmental parameters—including temperature, humidity, and dust levels—alongside electrical variables to develop robust predictive algorithms.

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Table 1. Comparative Reliability Metrics of Central Inverters in Large-Scale Solar Power Plants: Current Performance vs. Parameter Database Integratio

Parameter	**Current Performance (2024)**	**With Parameter Database (Projected)**
MTBF (Mean Time Between Failures)	4.2 years	6.1 years
MTTR (Mean Time to Repair)	36 hours	20 hours
Annual Energy Losses	1.8% (~31.5 GWh/100 MW)	0.9% (~15.7 GWh/100 MW)
Downtime Contribution	22% of outages	< 15% of outages
IRR Reduction	-1.5%	-0.5%

The results highlight that without a structured database for inverter reliability, Uzbekistan's solar sector risks substantial performance losses as capacity scales up to **18.5 GW by 2035**. By implementing centralized monitoring and diagnostic systems, the sector can mitigate risks and ensure smoother renewable integration. Furthermore, the parameter database has wider implications beyond solar, as it can be adapted for hybrid power systems that combine PV with wind, hydro, and battery storage. This positions Uzbekistan to lead in developing **data-driven early warning systems** for renewables in

Central Asia, ensuring long-term energy security and economic sustainability.

4. Conclusions

This study demonstrates that the creation of a parameter database for reliability assessment and early warning systems significantly enhances the operational stability of central inverters in Uzbekistan's large-scale photovoltaic (PV) plants. Analysis of field data revealed that inverter failures account for 22% of total downtime, primarily caused by semiconductor degradation, capacitor wear, and thermal issues under harsh climatic conditions. The integration of structured parameter databases enables continuous monitoring, predictive diagnostics, and data-driven maintenance scheduling, resulting in a projected MTBF improvement from 4.2 to 6.1 years and a 50% reductisson in annual energy losses. These findings confirm that implementing such systems can improve plant efficiency, extend equipment lifespan, and strengthen Uzbekistan's transition toward renewable energy leadership in Central Asia. Moreover, the developed framework provides a scalable foundation for integrating hybrid systems—combining PV, wind, and storage—thereby supporting the nation's 2030 green energy strategy and ensuring sustainable, resilient power infrastructure development.

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