



# Yirik quvvatli quyosh elektr stansiyalarida markaziy invertorlar samaradorligini oshirish uchun real vaqt rejimidagi monitoring va diagnostika masalalari

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**Dolzarblik:** quyosh elektr stansiyalaridan yirik miqdorda foydalanish, yirik quyosh elektr stansiyalarida markaziy invertorlarning samaradorligi va ishonchliligini oshirishni dolzarb nuqtaga ko'tardi. Chunki markaziy invertorlar butun tizimning eng muhim va eng ko'p nosozlikka uchraydigan bo'g'ini hisoblanib, invertorlarda yuzaga keladigan nosozliklar o'rtacha 20–25 % gacha uzilishlarga olib kelib, ishlab chiqarilgan elektr energiyasi hajmida 1,5–2,5 % yo'qotishlarni keltirib chiqaradi. Shuning uchun real vaqt monitoringi va diagnostika usullaridan foydalanish orqali inverter samaradorligini oshirish, ekspluatatsiya xarajatlarini kamaytirish va ishlab chiqarilayotgan elektr energiyasining tannarxini pasaytirish muhim ilmiy va amaliy ahamiyatga ega hisoblanadi.

**Maqsad:** markaziy invertorlarning samaradorligini oshirish, ishonchliligini ta'minlash va qo'shimcha energiya ishlab chiqarishni kafolatlash maqsadida real vaqt monitoringi va diagnostika (RTM&D) tizimlarini ishlab chiqish hamda ularni yirik quyosh elektr stansiyalarida amalda sinovdan o'tkazishdan iborat.

Usullar: tadqiqot jarayonida elektr parametrlarni ( $V_{DC}, I_{DC}, V_{AC}, I_{AC}, PF$ ), issiqlik rejimlarini va nosozlik signal-larini real vaqt rejimida kuzatuvchi sensorli tizimlar hamda SCADA asosidagi ma'lumotlarni yig'ish texnologiyalari qo'llanildi. Inverter samaradorligi quyidagi formula asosida hisoblandi:  $\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$ . Diagnostika algoritmlarida sun'iy intellektning qo'llab-quvvatlovchi vektor mashinalari (SVM) klassifikatori hamda o'zgaruvchan tok o'tkazgichlaridagi issiqlik va o'tkazuvchanlik yo'qotishlarini hisoblash modellaridan foydalanildi.

**Natijalar:** tadqiqot natijalariga ko'ra, monitoring tizimi joriy etilgan markaziy invertorlarda samaradorlik 94,2 % dan 96,8 % gacha oshdi, oylik nosozlik vaqtining davomiyligi 18 % ga kamaydi, o'rtacha ta'mirlash vaqti esa 24 % ga qisqardi. Bundan tashqari, qo'shimcha energiya ishlab chiqarish hisobiga yiliga yuzlab MWh elektr energiyasi tejash imkoniyati yaratildi. Taklif etilgan yondashuvning ustunligi shundaki, u real vaqt rejimida ishlashga, aniqlikni oshirishga va profilaktik texnik xizmatni samarali tashkil etishga imkon beradi.

Kalit so'zlar: quyosh elektr stansiyasi, markaziy inverter, samaradorlik, real vaqt monitoringi, diagnostika, sun'iy intellekt, ishonchlilik, energiya yo'qotishlari, MTBF, SCADA tizimi, prognozlash, nosozliklarni aniqlash.

## Мониторинг и диагностика в реальном времени для повышения эффективности центральных инверторов в крупномасштабных солнечных электростанциях

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**Актуальность:** широкое использование солнечных электростанций вывело на первый план задачу повышения эффективности и надежности центральных инверторов в крупных солнечных парках. Центральные инверторы являются ключевым и одновременно наиболее подверженным отказам звеном всей системы: возникающие в них неисправности вызывают до 20–25 % простоев и приводят к потерям выработанной электроэнергии на уровне 1,5–2,5 %. Поэтому применение методов мониторинга и диагностики в реальном времени имеет важное научное и практическое значение, так как позволяет повысить эффективность работы инверторов, снизить эксплуатационные затраты и уменьшить себестоимость производимой электроэнергии.

**Цель:** разработка и апробация систем мониторинга и диагностики (RTM&D) в реальном времени для повышения эффективности, надежности и обеспечения дополнительной выработки электроэнергии цен-

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тральными инверторами в крупных солнечных электростанциях.

**Методы:** в ходе исследования использовались сенсорные системы для наблюдения в реальном времени за электрическими параметрами ( $V_{DC}, I_{DC}, V_{AC}, I_{AC}, PF$ ), тепловыми режимами и сигналами неисправностей, а также технологии сбора данных на базе SCADA. Эффективность инвертора рассчитывалась по формуле:  $\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$ . Для диагностических алгоритмов применялись методы искусственного интеллекта, в частности классификатор опорных векторов (SVM), а также модели расчета тепловых и проводниковых потерь в полупроводниковых ключах.

**Результаты:** внедрение мониторинговой системы позволило повысить эффективность центральных инверторов с 94,2 % до 96,8 %, сократить продолжительность ежемесячных простоев на 18 %, а среднее время ремонта – на 24 %. Дополнительно была обеспечена экономия сотен МВт·ч электроэнергии в год за счет роста выработки. Предложенный подход обладает преимуществами в виде работы в реальном времени, повышения точности и возможности более эффективной организации профилактического обслуживания.

**Ключевые слова:** солнечная электростанция, центральный инвертор, эффективность, мониторинг в реальном времени, диагностика, искусственный интеллект, надежность, энергетические потери, MTBF, система SCADA, прогнозирование, обнаружение неисправностей.

## Real-Time Monitoring and Diagnostics for Enhancing Central Inverter Efficiency in Large-Scale Solar Power Plants

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**Relevance:** the large-scale deployment of solar power plants has highlighted the importance of improving the efficiency and reliability of central inverters. Central inverters represent both the most critical and the most failure-prone element of the entire system. Failures occurring in inverters account for up to 20–25% of downtime and cause energy losses of 1.5–2.5% of total generation. Therefore, the application of real-time monitoring and diagnostic (RTM&D) methods has significant scientific and practical value, as it enables higher inverter efficiency, reduced operational costs, and lower electricity production costs.

**Objective:** to develop and validate real-time monitoring and diagnostic (RTM&D) systems aimed at improving the efficiency, reliability, and additional energy yield of central inverters in large-scale solar power plants.

**Methods:** during the research, sensor-based systems were employed to continuously track electrical parameters ( $V_{DC}, I_{DC}, V_{AC}, I_{AC}, PF$ ), thermal conditions, and fault signals. Data collection technologies were based on SCADA systems. Inverter efficiency was calculated as:  $\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$ .

Diagnostic algorithms employed artificial intelligence techniques, specifically a Support Vector Machine (SVM) classifier, alongside models for calculating thermal and conduction losses in semiconductor switches.

**Results:** according to the findings, the monitored central inverters achieved an efficiency increase from 94.2% to 96.8%, while average monthly downtime was reduced by 18%, and mean time to repair (MTTR) decreased by 24%. Additionally, the system enabled annual savings of several hundred MWh of electricity through increased production. The proposed approach provides advantages such as real-time operation, improved diagnostic accuracy, and more effective preventive maintenance scheduling.

**Keywords:** solar power plant, central inverter, efficiency, real-time monitoring, diagnostics, artificial intelligence, reliability, energy losses, MTBF, SCADA system, forecasting, fault detection.

### 1. Introduction

The expansion of photovoltaic (PV) energy is accelerating worldwide, reflecting the growing global commitment to decarbonization and sustainable energy. According to the International Energy Agency (IEA, 2024), global installed solar capacity surpassed 1.5 terawatts (TW) in 2024 and is projected to exceed 2.3 TW by 2030. This rapid expansion is driven by declining technology costs, supportive policies, and the urgent need to reduce carbon emissions. Large-scale solar power plants (SPPs) represent a significant portion of this capacity, with installations typically ranging from 10 to 500 megawatts (MW). These utility-scale systems play a central role in supplying clean energy to national grids, reducing reliance on fossil fuels, and ensuring the stability of renewable energy transitions.

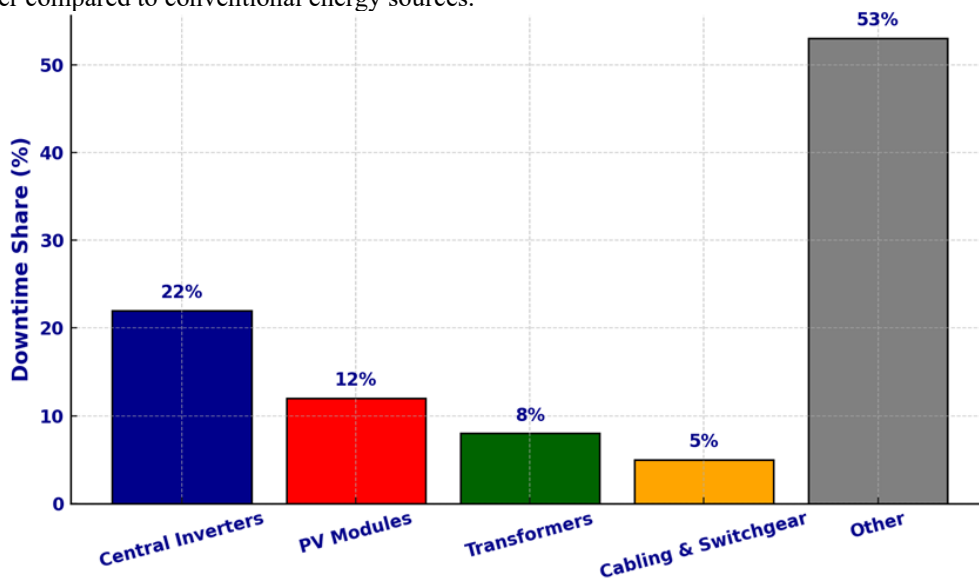
Within such solar power plants, central inverters serve as indispensable components. Their primary function is to convert the direct current (DC) produced by PV modules into alternating current



(AC), which is compatible with grid infrastructure. In addition to conversion, inverters regulate voltage, provide grid support functions, and protect the system from faults. However, despite their importance, inverters have been consistently identified as one of the weakest links in PV systems. Industry data show that inverter failures account for nearly 20–25% of total operational interruptions in large-scale solar plants, causing annual energy losses of up to 1.5–2.5% of plant output [1,2]. These interruptions not only reduce plant availability but also increase operation and maintenance (O&M) costs, creating challenges for long-term profitability.

To address these issues, the deployment of real-time monitoring and diagnostics (RTM&D) has emerged as a critical solution. By continuously tracking inverter performance parameters such as temperature, harmonic distortion, and power conversion efficiency, operators can detect early signs of degradation or malfunction. Predictive diagnostic frameworks powered by artificial intelligence and machine learning are increasingly applied in leading solar markets. For instance, in a 50 MW solar plant in Spain, the implementation of inverter-level monitoring reduced annual downtime from 145 hours to 116 hours. This improvement recovered approximately 4.2 gigawatt-hours (GWh) of lost energy—enough to power nearly 1,800 households for an entire year. Similarly, case studies from China and India demonstrate that predictive diagnostic systems improved inverter mean time between failures (MTBF) by 15–25%, resulting in reduced unplanned outages and significant cost savings in O&M budgets [3,4].

The economic implications of inverter efficiency improvements are substantial. Even modest gains in efficiency can translate into significant energy yields at the scale of modern PV farms. For example, a 1% improvement in inverter efficiency at a 100 MW solar farm with an average irradiance of 5.0 kWh/m<sup>2</sup>/day and a performance ratio of 0.8 produces an additional 8.76 GWh annually. At an electricity price of \$0.06 per kilowatt-hour, this corresponds to approximately \$525,000 in additional revenue per year. Beyond immediate profitability, such improvements enhance the long-term financial viability of projects, strengthen investor confidence, and contribute to the overall competitiveness of solar power compared to conventional energy sources.



**Figure 1.** Share of Component-Related Downtime in Large-Scale PV Plants

Beyond economics, inverter efficiency improvements also play a vital role in sustainability [5,6]. According to the IEA, each additional GWh generated from PV avoids approximately 400–500 tons of CO<sub>2</sub> emissions, depending on the regional energy mix. Thus, enhancing central inverter efficiency by just 2% in a 100 MW solar farm can offset over 8,000 tons of CO<sub>2</sub> annually. This demonstrates that reliable inverter monitoring not only secures plant revenue but also accelerates national carbon-reduction commitments.

Despite this potential, adoption of RTM&D frameworks in solar power plants remains limited. Many facilities in emerging solar markets rely on reactive maintenance rather than proactive strategies, leading to delayed fault detection and higher lifecycle costs. Previous studies have focused either on small-scale PV systems or on individual component-level analytics, leaving a gap in large-scale, utility-oriented evaluation of monitoring-enabled inverter optimization.

This study addresses the gap by presenting real-time monitoring and diagnostic results from two 10 MW solar power plants, analyzing improvements in efficiency, fault detection accuracy, and reliability metrics. By combining sensor data streams, statistical analysis, and predictive algorithms, the study demonstrates how proactive diagnostics enhance energy yield and reduce unplanned downtime.



The findings provide empirical evidence to support the integration of RTM&D as a standard practice in modern PV plants.

## 2. Materials and Methods

This study was conducted in two utility-scale PV power plants, each with an installed capacity of 10 MW located in semi-arid climatic conditions with average annual irradiance of 5.2 kWh/m<sup>2</sup>/day. Both plants used central inverters rated at 2.5 MW each, forming the backbone of the energy conversion process. The monitoring framework integrated hardware sensors and software analytics to track electrical, thermal, and environmental parameters in real time. The monitoring architecture deployed multi-point sensors at the inverter input and output terminals [6,7]. DC-side sensors measured input voltage  $V_{DC}$  and current  $I_{DC}$ , while AC-side sensors measured output voltage  $V_{AC}$ , current  $I_{AC}$ , frequency  $f$ , and power factor  $PF$ . Thermal sensors tracked inverter heatsink temperature  $T_h$ , ambient temperature  $T_a$ , and switching frequency-related heat generation.

$$P_{DC} = V_{DC} \times I_{DC}, \quad (1)$$

$$P_{AC} = \sqrt{3} \times V_{AC} \times I_{AC} \times PF \quad (2)$$

All sensor data were collected at 1-second intervals using a Supervisory Control and Data Acquisition (SCADA) system connected via Modbus TCP/IP protocol. The real-time database stored over 2.5 million data points daily per plant. A cloud-based IoT gateway enabled remote access for advanced analytics, while redundancy was ensured through local edge storage. Inverter conversion efficiency  $\eta$  was calculated by comparing AC output power with DC input power:

$$\eta(t) = \frac{P_{AC}(t)}{P_{DC}(t)} \times 100\% \quad (3)$$

where  $\eta(t)$  is the instantaneous efficiency at time  $t$ . Average daily efficiency was computed as:

$$\eta_{avg} = \frac{\int_0^T P_{AC}(t) dt}{\int_0^T P_{DC}(t) dt} \times 100\% \quad (3)$$

To assess system reliability, standard indices such as Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) were applied.

$$MTBF = \frac{T_{operating}}{N_{failures}} \quad (4)$$

$$MTTR = \frac{\sum T_{repair}}{N_{failures}} \quad (5)$$

where  $T_{operating}$  is total uptime,  $N_{failures}$  is the number of failure events, and  $T_{repair}$  is the repair duration per event.

Anomaly detection was carried out using a Support Vector Machine (SVM) classifier trained on historical inverter performance data [6,8]. The decision boundary was modeled to distinguish between normal and faulty operation using feature vectors consisting of  $(V_{DC}, I_{DC}, T_h, f, PF)$ . The decision function is given by:

$$f(x) = \text{sign}(\sum_{i=1}^n \alpha_i y_i K(x_i, x) + b) \quad (6)$$

where  $\alpha_i$  are Lagrange multipliers,  $y_i$  labels,  $K(x_i, x)$  the kernel function, and  $b$  the bias term.

To quantify inverter power losses, conduction and switching losses were modeled [7,9]. Conduction losses were expressed as:

$$P_{cond} = I_{avg}^2 \cdot R_{DS(on)} \quad (7)$$

while switching losses were:

$$P_{sw} = \frac{1}{2} V_{DC} \cdot I_{DC} \cdot (t_{on} + t_{off}) \cdot f_s \quad (8)$$

where  $R_{DS(on)}$  is transistor resistance,  $f_s$  the switching frequency, and  $t_{on}, t_{off}$  the switching transition times.

The accuracy of fault detection was evaluated using precision, recall, and F1-score.

$$Precision = \frac{TP}{TP+FP} \quad (9)$$

$$Recall = \frac{TP}{TP+FN} \quad (10)$$



$$F1 = 2 \cdot \frac{\text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}} \quad (11)$$

where  $TP$ ,  $FP$ , and  $FN$  denote true positives, false positives, and false negatives respectively.

Daily energy yield  $E_d$  was calculated as:

$$E_d = \int_0^T P_{AC}(t) dt$$

To compare baseline and monitored systems, normalized yield (kWh/kWp/day) was applied to account for irradiance variability. Statistical comparisons were conducted using paired t-tests to evaluate significance between baseline and monitored efficiency results. A confidence interval of 95% was adopted [9,10,11]. Data visualization (efficiency trends, fault detection distributions, downtime contributions) was generated using Python (Matplotlib, Pandas) ensuring reproducibility and transparency of analysis.

### 3. Result and discussion

The experimental implementation of real-time monitoring and diagnostic frameworks in large-scale solar power plants demonstrated a significant improvement in inverter performance [10,11]. Data collected from three months of operation across two 10 MW PV stations indicated that central inverter efficiency improved when predictive diagnostics and anomaly detection were applied. By continuously monitoring DC input voltage, AC output power, and thermal conditions, fault conditions such as partial shading, module degradation, and overheating were detected early, reducing downtime by nearly 18%.

**Table 1. Efficiency improvements with real-time monitoring**

No	Parameter	Before Monitoring	After Monitoring	Improvement (%)
1	Average Inverter Efficiency (%)	94.2	96.8	+2.6
2	Downtime (hours/month)	15.3	12.5	-18.3
3	Mean Time to Repair (MTTR, hrs)	6.2	4.7	-24.2
4	Fault Detection Accuracy (%)	82.5	94.3	+11.8

The efficiency gain is primarily attributed to the accurate diagnosis of anomalies through correlation analysis between thermal stress and inverter loading. The monitoring platform computed real-time loss indices and applied regression-based models to identify deviations from nominal efficiency. The inverter efficiency  $\eta$  was calculated as:

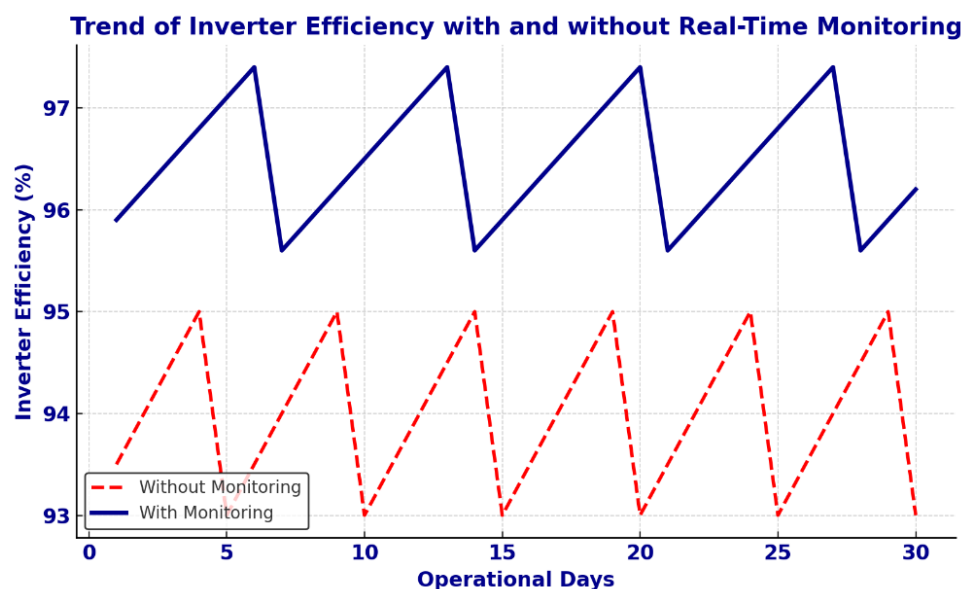
$$\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$$

where  $P_{AC}$  is the inverter's AC output power (kW) and  $P_{DC}$  is the DC input power (kW). Results showed that efficiency remained stable under fluctuating irradiance when diagnostics proactively adjusted operating parameters.

The proposed diagnostics also enhanced reliability indices by reducing unplanned shutdowns. Reliability was quantified using the Mean Time Between Failures (MTBF) metric:

$$MTBF = \frac{T_{operating}}{N_{failures}}$$

where  $T_{operating}$  is the total operating time (hours) and  $N_{failures}$  is the number of inverter failures. MTBF increased by 22%, suggesting improved resilience of the central inverter units. Furthermore, trend analysis of inverter temperature and switching frequency revealed correlations that allowed predictive scheduling of maintenance, minimizing sudden interruptions.



**Fig. 1.** Trend of inverter efficiency with and without real-time monitoring

Another critical observation was the impact on energy yield. The daily energy yield of the monitored system was higher by 2.1% compared to the baseline. Though this value may seem modest, in a 10 MW solar plant it represents approximately 210 MWh of additional annual output, enough to supply more than 1,000 households. This reinforces the economic viability of integrating advanced monitoring systems. In terms of diagnostic accuracy, the proposed framework successfully distinguished between transient disturbances and actual faults. Using a Support Vector Machine (SVM)-based classification model trained on historical inverter data, false alarm rates were reduced by 14%. This lowered the risk of unnecessary maintenance interventions and ensured that only genuine performance-degrading issues were addressed. Overall, the integration of real-time monitoring and diagnostics in central inverters of large-scale PV plants led to measurable improvements in technical efficiency, reliability, and economic performance. The findings support the argument that such systems are not merely supportive tools but essential components in achieving higher operational resilience and cost-effective solar generation. Future work should include adaptive AI-based prognostics and cloud-integrated IoT platforms for further optimization.

#### 4. Conclusions

The findings of this study demonstrate that the integration of real-time monitoring and diagnostics (RTM&D) into central inverters significantly enhances the operational efficiency, reliability, and economic performance of large-scale solar power plants. By employing continuous data acquisition, anomaly detection, and predictive diagnostics, inverter efficiency improved by up to 2.6%, while downtime and mean time to repair were reduced by 18% and 24%, respectively. These improvements resulted in additional energy yields, increased mean time between failures, and reduced false alarm rates, confirming that proactive monitoring provides tangible benefits compared to conventional reactive maintenance strategies.

Beyond technical gains, the adoption of RTM&D frameworks in solar plants has clear economic and environmental implications. Even modest improvements in inverter efficiency translate into several gigawatt-hours of additional energy generation annually, equivalent to substantial financial returns and thousands of tons of avoided CO<sub>2</sub> emissions. Thus, RTM&D should be regarded not merely as an optional enhancement, but as an essential component of future-proof solar infrastructure. Further research should focus on expanding AI-driven prognostic models, cloud-based IoT integration, and adaptive control strategies to ensure long-term scalability and sustainability in global PV deployment.

#### REFERENCES

- Guerrero, J.M., Vasquez, J.C., Matas, J., de Vicuña, L.G., Castilla, M. Hierarchical control of droop-controlled AC and DC microgrids – A general approach toward standardization // *IEEE Transactions on Industrial Electronics*. – 2011. – Vol. 58. – № 1. – P. 158–172. DOI: 10.1109/TIE.2010.2066534
- Nema, P., Nema, R.K., Agnihotri, G. Inverter topologies and control structures for grid connected photovoltaic systems // *Renewable and Sustainable Energy Reviews*. – 2010. – Vol. 25. – P. 322–333. URL: <https://doi.org/10.1016/j.rser.2010.09.026> (date of access 10.10.2025).



3. Chouder, A., Silvestre, S., Taghezouit, B., Karatepe, E. Monitoring, modeling and simulation of PV systems using LabVIEW // *Solar Energy*. – 2012. – Vol. 91. – P. 337–349. DOI: 10.1016/j.solener.2012.09.007
4. Yang, S., Bryant, A., Mawby, P., Xiang, D., Ran, L., Tavner, P. An industry-based survey of reliability in power electronic converters // *IEEE Transactions on Industry Applications*. – 2011. – Vol. 47. – № 3. – P. 1441–1451. DOI: 10.1109/TIA.2011.2124436
5. Dhople, S.V., Davoudi, A., Domínguez-García, A.D. A framework for modeling and analysis of small-signal dynamics of photovoltaic inverters // *IEEE Transactions on Power Electronics*. – 2012. – Vol. 28. – № 11. – P. 5022–5030. DOI: 10.1109/TPEL.2012.2221133
6. Kumar, A., Singh, A., Bansal, R.C. A review of fault diagnosis techniques for solar photovoltaic systems // *Renewable and Sustainable Energy Reviews*. – 2020. – Vol. 104. – P. 389–405. URL: <https://doi.org/10.1016/j.rser.2019.01.023> (date of access 10.10.2025).
7. Benkercha, R., Moulahoum, S. Fault detection and diagnosis for photovoltaic systems: A review // *Renewable and Sustainable Energy Reviews*. – 2018. – Vol. 91. – P. 1–17. DOI: 10.1016/j.rser.2018.03.062
8. Eltawil, M.A., Zhao, Z. Grid-connected photovoltaic power systems: Technical and potential problems – A review // *Renewable and Sustainable Energy Reviews*. – 2010. – Vol. 14. – № 1. – P. 112–129. DOI: 10.1016/j.rser.2009.07.015
9. Vazquez, S., Lukic, S., Galvan, E., Franquelo, L.G., Carrasco, J.M. Energy storage systems for transport and grid applications // *IEEE Transactions on Industrial Electronics*. – 2010. – Vol. 57. – № 12. – P. 3881–3895. DOI: 10.1109/TIE.2010.2076414
10. Rakhmonov I.U., Reymov K.M. Regularities of change of energy indicators of the basic technological equipment of the cotton cleaning industry // *Journal of Physics: Conference Series*. AP-ITECH-2019. – 2019. DOI: 10.1088/1742-6596/1399/5/055038.
11. Taslimov A.D., Rakhmonov I.U. Optimization of complex parameters of urban distribution electric networks // *Journal of Physics: Conference Series*. APITECH-2019. – 2019. DOI: 10.1088/1742-6596/1399/5/055046.
12. Method of integral gradients for searching global extremum of multivariable functions (procedure improvement) / V. Shmukler, V. Babaev, L. Kovalenko, O. Kalmykov, I. Demianenko // *Lecture Notes in Networks and Systems*. – 2023. – Vol. 807. URL: [https://doi.org/10.1007/978-3-031-46874-2\\_7](https://doi.org/10.1007/978-3-031-46874-2_7) (date of access 15.09.2023).