Yirik quyosh elektr stansiyalaridagi markazlashgan invertorlarning sun'iy intellektga asoslangan real vaqt monitoringi va ishonchliligini oshirish

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Dolzarblik: Ishonchlilik degradatsiyasi va nosozlik diagnostikasi cheklovlari yirik quyosh elektr stansiyalaridagi markazlashgan inverterlar barqarorligiga salbiy ta'sir koʻrsatadi.
Maqsad: Tadqiqotda SCADA, sun'iy intellekt va termik modellarga asoslangan real vaqtli monitoring, nosozlik diagnostikasi, ishonchlilik baholashi hamda nosozlikka bardoshli boshqaruv usullari tahlil qilinadi.
Usullar: Degradatsiya modellari, SCADA monitoringi, mashinaviy oʻrganish diagnostikasi va Neutral Point Shift kompensatsiya usullarining qiyosiy tahlili amalga oshirildi.
Natijalar: Gibrid monitoring yondashuvlari nosozliklarni aniqlash aniqligini oshirdi, avariyadan keyingi tiklanishni yaxshiladi va inverter ishonchliligini kuchaytirdi.
Kalit soʻzlar: markazlashgan inverter; nosozlik diagnostikasi; SCADA monitoringi; termik degradatsiya; mashinaviy oʻrganish; NPS kompensatsiyasi; ishonchlilik bahosi; quyosh elektr stansiyasi.

AI-ориентированный мониторинг технического состояния в реальном времени и повышение надежности централизованных инверторов крупных солнечных электростанций

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Актуальность: Деградация надёжности и ограничения диагностики неисправностей существенно влияют на устойчивость централизованных инверторов солнечных электростанций.
Цель: В работе исследуются современные подходы на основе SCADA, искусственного интеллекта и тепловых моделей для мониторинга состояния, диагностики неисправностей, оценки надёжности и отказоустойчивого управления централизованными инверторами.
Методы: Сравнительный анализ моделей деградации, SCADA-мониторинга, машинного обучения и методов компенсации Neutral Point Shift.
Результаты: Гибридные методы мониторинга повысили точность диагностики, обеспечили адаптивное восстановление после аварий и повысили эксплуатационную надёжность инверторов.
Ключевые слова: централизованный инвертор; диагностика неисправностей; SCADA-мониторинг; тепловая деградация; машинное обучение; компенсация NPS; оценка надёжности; солнечная электростанция.

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AI-Driven Real-Time Condition Monitoring and Reliability Enhancement of Centralized Inverters in Large-Scale Solar Power Plants

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Relevance: Reliability degradation and fault diagnosis limitations significantly affect centralized inverter stability in large-scale solar power plants.
Objective: This study investigates modern SCADA-, AI-, and thermal-model-based approaches for real-time condition monitoring, fault diagnosis, reliability assessment, and fault-tolerant operation of centralized inverters operating under dynamic renewable energy conditions.
Methods: Comparative analysis of degradation models, SCADA monitoring, machine learning diagnostics, and Neutral Point Shift compensation methods.
Results: Hybrid monitoring approaches improved fault detection accuracy, enabled adaptive post-fault recovery, reduced unplanned shutdown risks, and enhanced inverter operational reliability under variable operating conditions.
Keywords: centralized inverter; fault diagnosis; SCADA monitoring; thermal degradation; machine learning; NPS compensation; reliability assessment; solar power plant.

1. Introduction

Large-scale photovoltaic power plants are becoming one of the dominant renewable energy generation technologies worldwide due to increasing electricity demand and global decarbonization targets. In such systems, centralized inverters play a critical role in converting DC power generated by photovoltaic arrays into AC power suitable for grid integration. The operational reliability of centralized inverters directly affects power quality, energy conversion efficiency, grid stability, and the economic performance of solar power plants. Failures in inverter systems can lead to unplanned shutdowns, significant maintenance costs, power losses, and reduced operational lifetime. Modern scientific research on centralized inverter condition monitoring mainly focuses on monitoring operating parameters, early fault detection, remaining useful life estimation, intelligent operating mode analysis, and predictive maintenance technologies. In recent years, the integration of SCADA systems, sensor networks, big data processing techniques, artificial intelligence, and machine learning algorithms has significantly improved inverter reliability and monitoring accuracy [1–5].

However, existing research is often limited to monitoring individual parameters rather than providing a comprehensive evaluation of the inverter's technical condition. Many existing approaches do not fully address integrated reliability assessment, degradation prediction, and adaptive operational optimization under real industrial conditions. In large-scale solar power plants, inverter operating conditions continuously change due to irradiation fluctuations, thermal stresses, load variations, and environmental influences. Therefore, adaptive monitoring and intelligent diagnostic models remain important scientific challenges (Fig. 1).

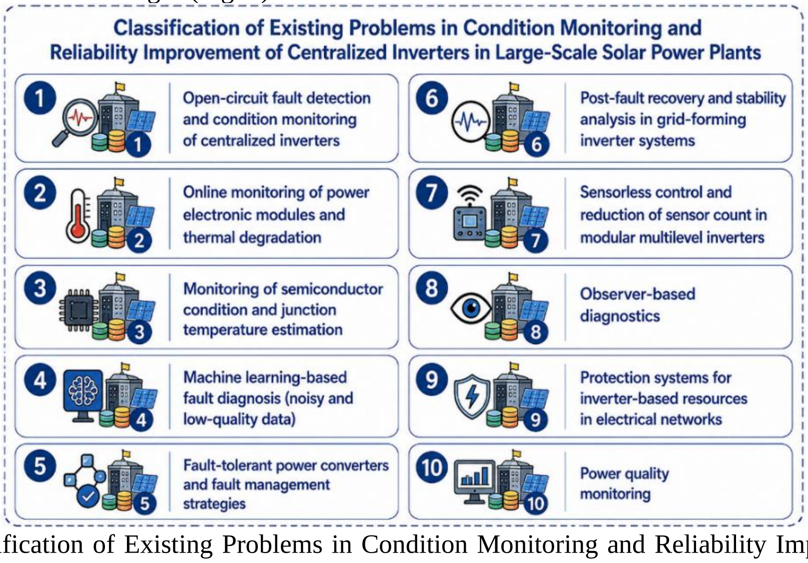

Fig. 1. Classification of Existing Problems in Condition Monitoring and Reliability Improvement of Centralized Inverters in Large-Scale Solar Power Plants

Scientific investigations in this field can generally be divided into several major research directions. The first direction involves open-circuit fault detection and condition monitoring in multilevel inverters. Universities such as Wuhan University, Central South University, University of Leeds, Seoul National University of Science and Technology, Vellore Institute of Technology, and Southeast University have conducted extensive studies supported by the National Natural Science Foundation of China, National Key Research and Development Program of China, and the National Research Foundation of Korea [6–8].

The second major focuses on online monitoring of power electronic module reliability and thermal degradation. Research performed at Delft University of Technology and Vrije Universiteit Brussel concentrates on IGBT overheating, thermal fatigue, and predictive diagnostics using advanced thermal models and reliability analysis techniques [9,10].

Another important area involves monitoring semiconductor operating conditions and estimating junction temperature. Aalborg University, Southeast University, and Hunan University have investigated thermal-sensitive electrical parameters to evaluate inverter degradation and reliability performance [11,12].

Machine learning-based fault diagnosis under noisy and low-quality data conditions has also become an important research trend. Nanyang Technological University demonstrated that artificial intelligence techniques can successfully identify inverter faults even under incomplete and noisy measurement conditions. These studies confirm the increasing importance of intelligent diagnostic technologies in renewable energy systems. The remaining research directions include fault-tolerant inverter topologies, grid-forming inverter post-fault recovery analysis, sensor reduction strategies, observer-based diagnostics, protection systems for inverter-based resources, and power quality monitoring techniques. Despite significant progress, many proposed methods still face challenges related to computational complexity, sensor dependency, industrial scalability, and real-time implementation.

2. Materials and Methods

This study analyzes modern methods for centralized inverter condition monitoring and reliability enhancement based on existing scientific investigations. The research methodology integrates physical degradation models, SCADA-based monitoring approaches, machine learning diagnostics, and adaptive fault-tolerant control methods.

The first part of the methodology focuses on inverter fault diagnosis and fault-tolerant operation. In centralized inverters, the most common reliability problems are open-circuit (OC) and short-circuit (SC) faults occurring in semiconductor switches and capacitors. These failures often lead to unexpected outages and severe economic losses. Modern fault management concepts divide the process into three stages: fault detection, fault isolation, and fault compensation [13–14].

A widely investigated fault-tolerant approach is the Neutral Point Shift (NPS) compensation method used in modular multilevel converters (MMC). In this method, faulty modules are isolated while healthy modules continue system operation. However, the resulting voltage imbalance between phases must be compensated through adaptive phase-angle redistribution algorithms (Fig. 2).

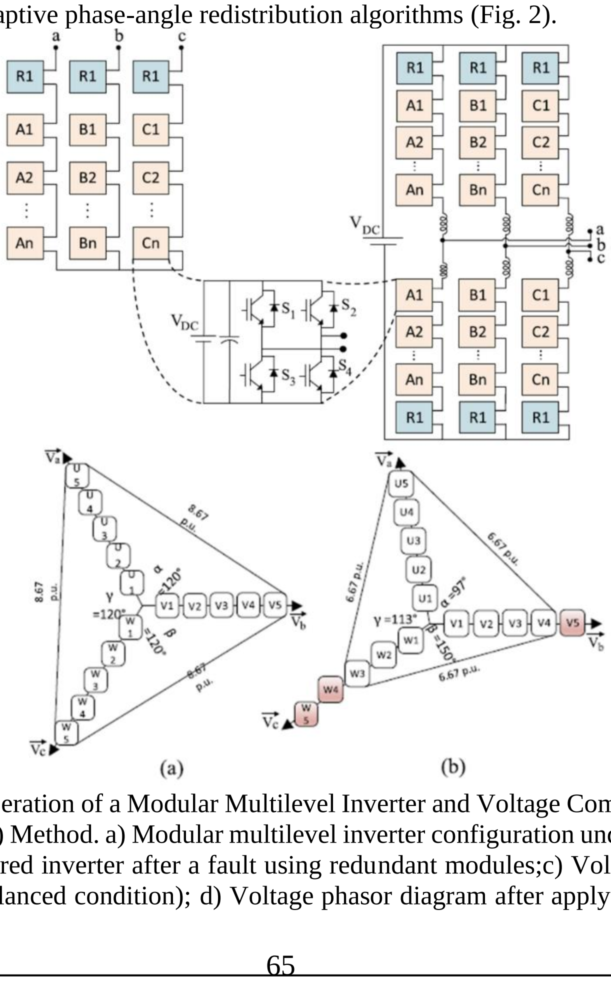

Fig. 2. Fault-Tolerant Operation of a Modular Multilevel Inverter and Voltage Compensation Using the Neutral Point Shift (NPS) Method. a) Modular multilevel inverter configuration under normal operating conditions; b) Reconfigured inverter after a fault using redundant modules;c) Voltage phasor diagram before the fault (120° balanced condition); d) Voltage phasor diagram after applying the NPS method (balance restored).

The NPS control method restores voltage balance after fault occurrence by modifying inverter control strategies and redistributing phase voltages dynamically. This enables the inverter to maintain stable operation even under partial failure conditions. Another important methodology involves reliability assessment based on physical degradation mechanisms. Thermal and mechanical stresses significantly accelerate degradation in power electronic components. The degradation growth rate can be expressed as:

$$\frac{dA}{dN} = C_1(\varepsilon_{pl})^{-C_2} \quad (1)$$

where $\frac{dA}{dN}$represents the degradation growth rate per thermal cycle, Adenotes the damaged area, $N$is the number of thermal cycles, $C_1$and $C_2$are empirical material coefficients, and ε_{pl}represents plastic deformation amplitude.

The service lifetime under thermal cycling conditions is evaluated using:

$$N_f = C_3(\Delta T)^{-C_4} \quad (2)$$

where $N_f$denotes the number of thermal cycles before failure, ΔTrepresents temperature fluctuation amplitude, and $C_3$and $C_4$are empirical thermal degradation coefficients.

These models enable quantitative degradation assessment and remaining useful life (RUL) estimation for inverter components.

Machine learning-based diagnostic techniques were also analyzed in this research. Artificial intelligence algorithms improve fault classification accuracy under noisy operating conditions. However, many machine learning methods require large volumes of high-quality operational data and significant computational resources.Table 1 summarizes major scientific directions related to centralized inverter monitoring and reliability improvement.

Table 1. Major Scientific Research Directions in Centralized Inverter Reliability Improvement

Research Direction	Universities	Funding Programs
Open-circuit fault detection	Wuhan University; University of Leeds	NSFC; National Key R&D Program
Thermal degradation monitoring	Delft University of Technology	HiEFFICIENT EU Program
Junction temperature estimation	Aalborg University	NSFC
Machine learning diagnostics	Nanyang Technological University	Singapore MOE Tier-1
Fault-tolerant inverter systems	Tallinn University of Technology	Estonian Research Council
Grid-forming inverter stability	Aalborg University; KTH	European Union
Sensorless MMC control	Yonsei University	NRF South Korea
Observer-based diagnostics	Université Libre de Bruxelles	University Funds
Protection systems	University of Toronto	Research Foundations
Power quality monitoring	Independent studies	Independent funding

3. Result and discussion

The analysis demonstrates that modern inverter reliability improvement methods significantly enhance operational stability, diagnostic accuracy, and fault tolerance in large-scale photovoltaic systems.

Table 2. Comparative Analysis of Existing Inverter Monitoring and Reliability Methods

Research Area	Achieved Results	Main Limitations
Open-circuit fault diagnosis	Fast and accurate detection	High computational complexity
Capacitor and IGBT monitoring	Early degradation estimation	Additional sensors required
Thermal degradation analysis	Lifetime prediction models	Mostly laboratory validation
Machine learning diagnostics	High accuracy under noisy data	High computational demand
Fault-tolerant inverter control	Continuous operation after fault	Additional hardware resources
Grid-forming inverter recovery	Stability enhancement	Limited applicability
Sensorless MMC control	Reduced sensor dependency	Limited fault coverage
Adaptive diagnostics	Improved monitoring flexibility	Difficult industrial generalization
Protection and power quality analysis	Comprehensive system evaluation	Insufficient automatic diagnostics

Open-circuit fault detection methods achieved rapid and accurate identification of inverter faults, reducing diagnostic time and preventing catastrophic failures. However, many approaches strongly depend on precise mathematical models and become computationally complex under varying operating conditions. Online monitoring of capacitors and semiconductor components enables early estimation of IGBT degradation and capacitor aging. Nevertheless, most methods require additional sensors or dedicated operating modes, which complicates industrial implementation.

Thermal degradation models successfully estimate inverter service lifetime and degradation evolution. These models provide quantitative reliability assessment and remaining useful life prediction. However, accurate parameter identification remains difficult because material properties vary significantly under real industrial conditions. Machine learning-based diagnostic systems demonstrated high fault detection accuracy even under noisy and incomplete data conditions. Artificial intelligence algorithms significantly improve adaptive diagnostics and predictive maintenance capabilities. Despite these advantages, large-scale deployment remains challenging because real-time AI systems require high-performance computing infrastructure and extensive training datasets. Table 2 summarizes the advantages and limitations of existing scientific approaches.

Existing SCADA-based monitoring systems often provide reactive responses to degradation rather than predictive intelligence. Furthermore, machine learning approaches frequently encounter adaptation problems under real industrial operating conditions. Consequently, early-stage degradation detection, accurate lifetime estimation, and optimal post-fault operation remain unresolved challenges.

The analysis also shows that many proposed methods were validated mainly under laboratory conditions rather than real large-scale solar power plants with rapidly changing operational regimes. Therefore, there is still strong demand for adaptive, sensor-reduced, hybrid monitoring systems combining physical models and data-driven artificial intelligence approaches.

The most promising future direction involves integrating SCADA systems, machine learning algorithms, thermal degradation models, and fault-tolerant control techniques into unified real-time monitoring platforms. Such systems can provide adaptive diagnostics, predictive maintenance, remaining useful life estimation, and optimized fault recovery simultaneously.

Conclusions. This study analyzed modern scientific approaches for condition monitoring and reliability enhancement of centralized inverters in large-scale solar power plants. The investigation demonstrated that SCADA systems, thermal degradation models, machine learning diagnostics, and fault-tolerant inverter control significantly improve operational reliability and diagnostic performance. Open-circuit fault diagnosis, thermal monitoring, junction temperature estimation, and artificial intelligence-based diagnostics provide important capabilities for predictive maintenance and early degradation detection. However, many existing approaches remain limited by high computational complexity, dependence on additional sensors, laboratory-based validation, and difficulties in industrial implementation. The results indicate that future inverter monitoring systems should integrate adaptive control algorithms, sensor-reduced architectures, physics-based degradation models, and machine learning methods into unified hybrid frameworks capable of operating in real time under dynamic industrial conditions. The development of intelligent hybrid monitoring systems will play a critical role in improving the reliability, efficiency, and operational stability of next-generation renewable energy systems.

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