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Optimization and Technological Innovation Path of Photovoltaic System Field Management from the Perspective of Electrical Engineering

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Abstract: Driven by the "Dual Carbon" strategy and green building concepts, the full utilization of idle rooftops, vacant lots, and parking lots for deploying distributed photovoltaic (PV) systems has become a key measure to enhance land and building utilization value. From the core perspective of electrical engineering, this paper systematically constructs a technical framework integrating "planning-operation-maintenance-guarantee" to address practical challenges such as low energy management efficiency and poor system coordination in diverse application scenarios. The study focuses on optimizing PV system operation mechanisms based on maximum power point tracking (MPPT), proposing integrated PV-storage capacity matching models and dynamic energy management strategies applicable to parking lots and idle spaces. It designs an online monitoring system for distributed PV with IoT sensors and modular emergency/replenishment power supply solutions. Additionally, it explores intelligent operation and predictive maintenance technologies leveraging digital twin and deep learning algorithms. Research and practice demonstrate that comprehensive application of these technologies in system design, electrical safety, and smart scheduling significantly improves field management precision, operational reliability, and lifecycle economic efficiency of distributed PV systems across multiple scenarios. This provides clear technical pathways and practical references for unlocking the value of idle assets and promoting green, low-carbon transformation in building and land utilization.

Keywords: New energy photovoltaics; Distributed photovoltaics; Idle resource utilization; Technical optimization

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1. Introduction

With the promulgation of the "Guidelines on Promoting the Safe and Reliable Construction of Distributed Photovoltaic Power Generation (2023)" and the national push for renewable energy adoption, the utilization of idle rooftops, vacant land, and parking lot canopies for distributed photovoltaic (PV) systems has garnered significant attention. In these diverse scenarios, specific technical requirements exist across power grid integration needs, electrical safety standards, and the integration of PV systems with existing buildings/environment. From an electrical engineering perspective, whether constructing efficient PV system topologies or establishing capacity matching models for integrated PV-storage systems, the core objective remains enhancing on-site management efficiency, operational reliability, and economic benefits of distributed PV. The policy's introduction provides robust support for these technical efforts, driving large-scale and high-quality development of distributed PV in various idle resource scenarios. Building on this foundation, this paper aims to systematically analyze and explore key technical compatibility and management optimization pathways for distributed PV across diverse application scenarios from an electrical engineering perspective, addressing critical issues such as energy efficiency in project development and operation, system safety and stability, and maintenance cost control.

2. Working mechanism of distributed photovoltaic and diversified application scenarios

2.1. Analysis of electrification characteristics and requirements in diversified scenarios

When deploying distributed PV systems on large idle rooftops or vacant lots, ensuring reliable power transmission and local consumption becomes critical [1]. These scenarios typically involve industrial facilities, warehouses, or future planned electric equipment (e.g., charging stations) that require stable and potentially growing power supply, demanding high grid access capacity, power quality, and system reliability. For applications like parking lot solar shelters, electrical safety standards are particularly stringent. Given the open environment and frequent human/vehicle traffic, PV systems and their supporting structures must feature excellent insulation, lightning protection grounding, and mechanical safeguards to prevent accidents such as electric shocks and short circuits, ensuring both personal and property safety. New energy PV systems integrated into these environments must meet specific technical requirements, including structural load-bearing capacity, aesthetic harmony, and complementary replacement of existing power loads. They must also comply with strict electrical regulations to achieve stable and reliable co-operation with existing distribution networks and electrical infrastructure.

2.2. Theoretical framework of light-load-storage coordinated operation

From an electrical engineering perspective, constructing a distributed PV system topology based on maximum power point tracking (MPPT) technology is crucial for revealing the dynamic coupling mechanism between load demand and PV power generation under microgrid architectures. MPPT technology ensures PV arrays maintain maximum power output under varying sunlight and environmental conditions, thereby improving energy utilization efficiency. The system topology built upon this foundation organically integrates PV power generation, diversified loads (such as building electricity consumption, electric vehicle charging stations), and energy storage devices. In microgrid architectures, the time-varying characteristics of loads and the intermittency/volatility of PV power generation interact with each other, creating a complex and critical dynamic coupling mechanism. In-depth research on this mechanism enables better coordination of energy flows among sources, loads, and storage, achieving efficient local energy utilization and optimized distribution [2]. For example, during periods of sufficient sunlight, PV power primarily meets local load demands, with excess energy stored in storage devices or fed into the grid. Conversely, during periods of insufficient sunlight or peak load times, energy storage devices or the grid supplement power supply to ensure system continuity and economic viability.

3. Research on photovoltaic technology adaptability in diversified scenarios

3.1. Optimization of light storage configuration in complex scenarios

In scenarios such as parking lots and vacant lots, load characteristics often exhibit diversity (e.g., base lighting, impact loads from EV fast-charging stations), imposing higher requirements on energy supply stability, power quality, and economic efficiency. To address this, a capacity matching model for integrated PV-storage systems must be established, tailored to building/site characteristics. This model should comprehensively consider factors including roof/vacant area availability, load capacity, local sunlight resources, and typical load curves (particularly power demand characteristics of charging stations) to accurately calculate PV installation capacity and energy storage system configurations, ensuring rational alignment of PV-storage-load [3]. Additionally, a dynamic energy management strategy based on load forecasting and electricity price signals is proposed. This strategy can coordinate PV output, energy storage charging/discharge behaviors, and load switching in real-time or proactively, charging storage during off-peak hours or PV surplus, and discharging energy storage during peak loads or high electricity prices. This achieves peak shaving, valley filling, improved self-sufficiency rates, and cost savings, ultimately ensuring stable, efficient, and economical energy supply in complex application scenarios.

3.2. Development of distributed photovoltaic intelligent monitoring system

In scenarios where distributed PV systems are widely deployed, developing efficient intelligent monitoring systems is crucial. This requires designing online monitoring devices that integrate multiple types of sensors (such as current/voltage sensors, temperature sensors, and irradiance meters) with IoT communication technologies. Such devices enable effective collaborative management of PV array operational status and building/site information. Leveraging IoT's high-efficiency data transmission and remote control capabilities, centralized, real-time, and precise monitoring can be achieved for PV arrays distributed across various locations (e.g., multiple idle rooftops). Key parameters include panel temperature, output power, inverter status, and environmental irradiance. Through continuous collection, analysis, and visualization of these massive operational data, maintenance personnel can promptly identify potential equipment failures (such as hot spots or string faults), evaluate system performance, and implement targeted maintenance. Simultaneously, the system can collaborate with building management systems or site monitoring platforms to provide data support for optimizing overall energy scheduling and assessing asset power generation efficiency, thereby achieving refined and intelligent management of distributed PV assets [4].

4. Operation and maintenance of distributed photovoltaic systems and emergency support system

4.1. Flexible energy supply and energy storage system design

4.1.1. Modular photovoltaic power generation and emergency backup system

To address specific needs such as temporary power supply, system capacity expansion, or regional energy independence, modular, mobile, or rapidly deployable PV units (e.g., PV mobile units or prefabricated modular systems) can be developed. These systems should integrate quick deployment or plug-and-play interface mechanisms to ensure rapid power generation when required, enhancing deployment flexibility and meeting emergency backup or elastic expansion needs. Additionally, they should incorporate efficient multi-stage inverter and grid/off-grid switching technologies to ensure output power quality complies with relevant standards [5]. These systems must also enable smooth transitions with fixed PV installations or local grids, providing uninterrupted or supplementary power support for critical loads. This approach improves the resilience and reliability of distributed PV systems in responding to emergencies or load fluctuations.

4.1.2. Optimization of hybrid energy storage system

Developing hybrid energy storage architectures (e.g., supercapacitor-lithium battery systems) tailored to diverse load characteristics is crucial for enhancing power quality and operational stability in distributed PV systems. Supercapacitors, with their high power density and rapid response, effectively mitigate PV power fluctuations and handle instantaneous high-power demands from shock loads like electric vehicle charging stations [6]. Lithium batteries, boasting high energy density, excel in time-of-use energy transfer and extended-duration power supply. By leveraging their complementary strengths and implementing customized power compensation and energy scheduling strategies, hybrid systems can dynamically adjust charging/discharging patterns based on real-time system conditions, enabling hierarchical management of power and energy demands. This optimized hybrid energy storage approach significantly improves distributed PV systems' performance when handling variable loads, ensures reliable power supply for critical applications, and extends the lifespan of energy storage equipment.

4.2. Smart power supply and energy dispatching technology

4.2.1. Multi-source collaborative optimization control algorithm

In the intelligent power dispatching technology of PV power supply systems, the multi-source collaborative optimization control algorithm plays a pivotal role [7]. This algorithm develops dynamic energy management strategies that consider multiple factors including electricity prices, load priorities, and user preferences, thereby achieving multi-objective optimization coordination among PV systems, energy storage, adjustable loads, and the grid. Through this algorithm, the system can automatically determine optimal operating modes based on real-time monitoring data and predictive information. For instance, during peak electricity demand periods, it prioritizes PV power generation and energy storage discharge while suppressing non-critical loads. When predicting insufficient PV output during rainy weather, it preemptively schedules energy storage charging or adjusts load operation plans. This intelligent coordinated control not only maximizes system economic efficiency but also enhances grid compatibility, ultimately improving overall energy utilization efficiency.

4.2.2. Rapid isolation and reconstruction strategies for system failures

In the intelligent operation and maintenance of PV systems, rapid fault isolation and reconstruction strategies are critical [8]. A protection and self-healing mechanism based on fast shutdown and island detection technology must be established to ensure personal safety and uninterrupted power supply for critical equipment. When faults (such as insulation failures, overcurrents, etc.) or grid abnormalities are detected, protective devices should act swiftly to precisely isolate fault points and prevent escalation. Simultaneously, based on predefined reconstruction logic, static transfer switches and similar equipment should be utilized to rapidly reconstruct the power supply network in non-fault areas, enabling smooth mode transitions (e.g., from grid-connected to off-grid operation). This ensures continuous power supply for critical loads within the system, minimizes operational impacts from faults, and enhances system availability and safety.

5. Engineering practice and technical optimization path

5.1. Photovoltaic and building/environment integrated technology

5.1.1. Structural synergy and safety design method

In PV field management from an electrical engineering perspective, structural coordination and safety design between PV systems and buildings/environment form the foundation. Integrated design and installation standards for PV support structures must be established for various carriers (e.g., concrete roofs, color-coated steel roofs, parking lot canopies, ground-mounted brackets). These standards should comprehensively consider factors such as the structural load-bearing capacity, wind pressure resistance, snow load resistance, and corrosion environment of the carriers to ensure the structural safety and long-term stability of PV systems [9]. Simultaneously, the design should balance installation and maintenance convenience, cost-effectiveness, and minimize impact on the original building's functionality and environmental aesthetics. Through such structural coordination design, a harmonious integration of safety, reliability, economy, and aesthetics can be achieved, laying a solid foundation for the smooth implementation and long-term stable operation of distributed PV projects.

5.1.2. Safe and reliable electrical connection and protection technology

In distributed PV integration, secure and reliable electrical connections coupled with comprehensive protection technologies are critical. On one hand, it is essential to develop and apply weather-resistant, corrosion-resistant, and highly reliable PV wiring systems and connectors suitable for various installation environments (e.g., high-temperature and humid roofs, vibration-prone carports), ensuring long-term stability and safety of electrical connections under harsh conditions. Waterproofing, dustproofing, and UV aging protection for connection points must strictly adhere to the highest standards. On the other hand, a robust electrical safety protection system must be established, including but not limited to proper grounding system design, precise insulation coordination, reliable lightning and surge protection, as well as necessary arc fault detection and rapid disconnection functions. This comprehensive approach ensures electrical safety throughout the system's lifecycle, preventing accidents such as fires and electric shocks [10].

5.2. Development of intelligent operation and maintenance management system

5.2.1. Digital twin platform development

From an electrical engineering perspective, the digital twin platform for distributed PV systems serves as the cornerstone of intelligent operation and maintenance. By establishing a lifecycle management platform that integrates Building Information Modeling (BIM), Geographic Information Systems (GIS), real-time/historical power generation data, and equipment status data, it enables precise mapping and bidirectional interaction between physical systems and virtual models. Leveraging the 3D visualization, data integration, and simulation capabilities of digital twin technology, managers can intuitively grasp the global distribution and real-time operational status of distributed PV assets, accurately locate faults, and analyze root causes. The platform also supports system performance evaluation, operational strategy optimization, and maintenance plan simulation based on the model. By bridging energy flow and information flow, it provides robust support for refined and predictive asset management, ultimately enhancing operational efficiency and return on investment.

5.2.2. Application of predictive maintenance algorithm

In PV field management, data-driven predictive maintenance algorithms are essential for reducing operational costs and improving system availability. These models, built on machine learning techniques (e.g., deep learning, time series analysis), evaluate the health status and predict failures of critical components like modules, inverters, and cable connections. Trained with historical operational data (current, voltage, power, insulation resistance), environmental metrics (temperature, humidity, irradiance), and maintenance records, they learn equipment degradation patterns and early warning signs. By comparing real-time data with predictive models, potential risks, such as abnormal module performance, loose connections, or inverter anomalies, can be identified early. The system generates alert tickets to guide maintenance teams in targeted interventions, shifting from reactive repairs to proactive protection. This approach effectively prevents power generation losses and severe equipment damage, ultimately extending system lifespan.

5.3. Standard system and safety assurance

5.3.1. Comprehensive electrical safety protection standards

From an electrical engineering perspective, establishing a comprehensive electrical safety standard system covering all distributed PV scenarios serves as the cornerstone for the industry's healthy development. It is essential to formulate and refine safety technical specifications for system design, equipment selection, installation acceptance, and operation maintenance across various application scenarios (residential, commercial, industrial, parking lots, etc.). Key aspects include system grounding and equipotential bonding standards, insulation resistance monitoring requirements, DC arc fault detection and interruption requirements, anti-reverse current and island protection configurations, as well as interconnection requirements with building fire protection systems. Through standardized safety constraints, potential hazards can be minimized to the greatest extent, ensuring the safety of personnel and property, and promoting the standardized and sustainable development of the distributed PV market.

5.3.2. Optimization of intelligent emergency response mechanism

From an electrical engineering perspective, optimizing emergency response mechanisms for distributed PV systems is a critical component in enhancing system resilience. It is essential to refine contingency plans covering various typical faults (such as equipment failures, grid anomalies, and natural disasters). These plans should clearly define fault reporting procedures, on-site response protocols, personnel assignments, and safety measures, with regular drills conducted. Conversely, the data analysis and remote control capabilities of intelligent operation and maintenance platforms should be fully utilized to establish rapid response processes based on real-time status awareness and intelligent decision-making. When system anomalies occur, the platform can automatically trigger alerts, conduct preliminary fault analysis, and assist in generating or executing partial handling commands (e.g., remotely isolating fault points). This significantly improves the speed and accuracy of emergency responses, minimizing outage duration and losses to the greatest extent.

6. Conclusion

From an electrical engineering perspective, advancing high-quality development of new energy PVs in scenarios like idle rooftops, vacant lots, and parking lots requires meticulous on-site management and technological innovation. This paper systematically explores and proposes a comprehensive technical approach encompassing "source-load-storage coordination, intelligent operation and maintenance, and safety assurance." Practical experience demonstrates that through deep integration and application of technologies such as maximum power point tracking, PV-storage coordinated configuration, IoT monitoring, digital twin, and predictive maintenance, distributed PV systems can effectively enhance energy output, operational reliability, safety levels, and lifecycle economics. The evolutionary path of distributed PV systems based on digital grid and intelligent technology development represents a crucial exploration aligning with energy revolution trends. The primary contribution of this paper lies in systematizing and contextualizing electrical engineering technologies for diverse distributed PV implementation scenarios. The proposed models, strategies, and system solutions provide practical technical support and operational guidance for unlocking the value of customers' idle assets and achieving green, low-carbon transformation in building and land utilization. Continuous innovation and integrated application of these technologies will not only improve on-site management of distributed PVs but also inject strong momentum into building new power systems and realizing sustainable development goals.

Disclosure statement

The author declares no conflict of interest.

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