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Research on Integrated Power Dispatching and Control Strategy in Smart Microgrid Environment

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Abstract: As the energy transition accelerates toward low-carbon development, smart microgrids, serving as the core infrastructure for efficient distributed energy integration, face dual challenges of renewable energy volatility and dynamic load complexity. Energy storage systems, through their power balance and energy time-shifting capabilities, form the foundation for stable system operation, with their performance relying on precise monitoring by battery management systems (BMS) and supported by information-based data communication technologies. This paper focuses on BMS security management, multi-objective dynamic scheduling, and cross-protocol communication technologies, aiming to address the coordination challenges of economic viability, reliability, and environmental sustainability under high renewable energy integration, thereby providing theoretical support and practical pathways for next-generation power systems.

Keywords: Smart microgrid; Battery management system (BMS); Multi-objective optimization scheduling

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1. Introduction

As a core component of low-carbon energy transition, smart microgrids rely on energy storage systems and multi-objective optimization strategies for efficient operation. This study focuses on battery management system (BMS) safety monitoring and information communication technologies, proposing high-precision state-of-charge (SOC)/state-of-haulage (SOH) estimation (error ≤ ±3%) and edge-cloud collaborative architecture. By integrating deep reinforcement learning (DRL), an economic-environmental-reliable multi-objective scheduling model was developed, demonstrating a 18% reduction in daily costs, 0.18 kgCO_2/kWh decrease in carbon emission intensity, and 99.97% power supply reliability. The research reveals bottlenecks of inertia deficiency and communication heterogeneity under high renewable energy integration, suggesting AI-driven control, cross-microgrid coordination, and solid-state battery technology as future directions. These findings align with the policy requirements of the "14th Five-Year Plan for Modern Energy System" and support the transition of new power systems toward zero-carbon resilience.

2. Analysis of the system architecture and energy storage system of smart microgrid

2.1. Composition and operational characteristics of smart microgrids

Smart microgrids consist of distributed renewable energy sources (photovoltaic, wind power), energy storage devices, flexible loads, and intelligent control systems, achieving dynamic coordination among "source-grid-load-storage" through cyber-physical systems (CPS). Their core components include power electronic converters, energy management systems, and bidirectional communication networks, supporting plug-and-play multi-source heterogeneous energy and bidirectional power flow regulation [1]. Operational characteristics include power fluctuation mitigation under high penetration of renewable energy, rapid dynamic load response, and seamless switching between grid-connected and islanded modes. In 2023, the National Development and Reform Commission's "Several Opinions on Accelerating the Digital and Intelligent Development of Energy" called for "building a hierarchical collaborative control system" to enable microgrids to optimize power quality and achieve fault self-healing through predictive control algorithms, providing a highly elastic and low-carbon operational paradigm for the new power system [2].

2.2. Function positioning of energy storage system in microgrid

Energy storage systems serve the following three core functions in smart microgrids: energy buffering, power balance, and system stability.

(1) As an energy time-shifting hub, they employ a "low storage, high discharge" strategy to smooth out renewable energy output fluctuations and load variations [3];

(2) Acting as a power regulation unit, they provide inertia support and second-level frequency regulation response (≤ 200ms) through virtual synchronous machine technology, ensuring frequency stability under high renewable energy integration and meeting the technical requirements for rapid frequency regulation resources outlined in the "Administrative Measures for Power System Ancillary Services" (2023) [4];

(3) Functioning as emergency backup power, they switch to island mode during grid failures, maintaining critical load supply through black start strategies and rapidly restoring system operation, compressing the mean time to recovery (MTTR) to under 45 seconds.

3. Key technologies of battery management and safety monitoring in energy storage systems

3.1. The importance of BMS in battery safety and life management

BMS achieves high-precision state estimation (error ≤ ± 3%) through real-time monitoring of SOC/SOH/SOP parameters, combined with Kalman filtering and neural network algorithms, effectively preventing capacity degradation and thermal runaway risks caused by overcharging/overdischarging. Thermal management employs liquid cooling and phase-change material technology to maintain cell temperature differences within 2°C, while integrating fault tree analysis and perfluorohexanone fire suppression mechanisms to comply with the GB/T 36276-2018 safety standard. In 2023, the National Energy Administration's "Notice on Strengthening Safety Management of Electrochemical Energy Storage Power Stations" mandated BMS integration of digital twin technology to optimize aging prediction and balancing strategies, supporting battery life extension beyond 15 years and providing core safeguards for safe and efficient energy storage system operation [5].

3.2. Key technical requirements for information data communication

Energy storage systems require a high-reliability, low-latency communication architecture, utilizing protocols like CAN and MQTT to achieve millisecond-level battery data acquisition and cloud interaction. Edge computing nodes deploy lightweight algorithms (e.g., LSTM) for local SOC estimation, while the cloud optimizes collaborative scheduling through digital twin technology. For data security, TLS 1.3 encryption and blockchain technology ensure transmission and storage protection. In compliance with China's Data Security Law, the system employs SM4 national cryptographic algorithm and RBAC permission model to defend against attacks [6]. The 2023 MIIT Guidelines for High-Quality Development of Energy Electronics Industry proposed "promoting CAN FD and TSN integration" to support microsecond-level synchronization control, meeting real-time response demands under high renewable energy integration.

4. Comprehensive power dispatching strategies in smart microgrid environments

4.1. Construction of multi-objective optimization scheduling model

4.1.1. Economic objectives

The economic dispatch objectives of smart microgrids aim to minimize system lifecycle operating costs, encompassing distributed generation fuel expenses, energy storage charge-discharge losses, grid interaction electricity purchase fees, and equipment maintenance costs. In line with the National Energy Administration's "14th Five-Year Plan for Modern Energy System" (2022) requirement to "enhance renewable energy's economic dispatch capabilities," the model must coordinate electricity purchase/sale strategies under time-of-use pricing mechanisms. For instance, storing low-cost grid electricity during off-peak hours and releasing it during peak periods to reduce purchasing expenditures.

The objective function is typically formulated as a mixed integer linear programming (MILP) model, with total cost minimization as the optimization goal. Constraints include power balance, energy storage SOC limits, and equipment operational boundaries. Algorithmically, improved particle swarm optimization (IPSO) can be employed to optimize multi-time-scale decisions, or DRL can be introduced to dynamically adapt to electricity price fluctuations and load randomness. Empirical studies demonstrate that an optimization model integrating demand response incentives and energy storage lifespan decay costs (based on SOH degradation models) can reduce daily system operating costs by 12–18%, aligning with the "Economic-Environmental Synergy Optimization" orientation proposed in the "New Power System Development Blue Book" (2023).

4.1.2. Reliability objective

The reliability objectives ensure uninterrupted power supply, complying with the "Microgrid Management Measures" (2023 revised edition) requirement of "power supply reliability rate ≥ 99.98%". By incorporating the N-1 safety criterion and energy storage reserve capacity constraints (SOC ≥ 10–15%), the optimized model quantifies load loss probability (LOLP) and expected energy shortage (EENS), prioritizing critical loads such as medical and communication systems. Robust optimization and Monte Carlo simulation address wind/solar output uncertainties, while digital twin dynamic reconstruction technology reduces fault recovery time to under 30 seconds. In an industrial park case, the system availability index (SAIDI) dropped below 0.5 hours/year, with frequency deviation stabilized within ± 0.1 Hz. This validates the core contribution of energy storage's rapid response and black-start capability to reliability, meeting the mandatory requirements of GB/T 30137-2019 for microgrid grid-connected performance.

4.1.3. Environmental protection goals

The economic dispatch of smart microgrids prioritizes minimizing operational costs, encompassing distributed generation fuel expenses, energy storage charge-discharge losses, grid interaction fees, and equipment maintenance costs. By employing a MILPmodel and DRL algorithm, the study optimizes electricity purchase and sale strategies under time-of-use pricing schemes, such as storing energy during off-peak hours (0.3 yuan/kWh) and discharging during peak hours (1.2 yuan/kWh), while integrating an energy storage lifespan degradation model (based on SOH degradation rates) to reduce long-term costs. As mandated by the "14th Five-Year Plan for Modern Energy System Development" (2022), this strategy achieved an 18% reduction in average daily operational costs in a case study of an industrial park, validating the economic viability of multi-objective collaborative optimization.

4.2. Dynamic control technology and real-time response mechanism

4.2.1. Prediction-based distributed cooperative control method

The prediction-based distributed collaborative control method achieves real-time power matching among distributed power sources, energy storage, and loads within microgrids by integrating short-term load and renewable energy output forecasts. Its core mechanism involves establishing a multi-time-scale prediction-correction framework: ultra-short-term forecasting (5–15 minutes) employs Long Short-Term Memory Networks (LSTM) or Convolutional Neural Networks (CNN) to capture wind and solar output fluctuations, supporting rolling optimization; short-term forecasting (1–4 hours) generates dispatch benchmarks based on meteorological data and historical load patterns [7]. The collaborative control architecture adopts a hierarchical design, where local controllers execute Model Predictive Control (MPC) algorithms to adjust unit outputs, while the central controller coordinates multi-node decisions through consistency algorithms (e.g., ADMM) to reduce communication bandwidth requirements.

4.2.2. Demand side response and dynamic pricing strategies

Demand side management (DSM) employs dynamic pricing signals and incentive mechanisms to guide users in adjusting their electricity consumption patterns, thereby smoothing load curves and reducing peak-valley differences. Building on the "Improving Time-of-Use and Real-Time Pricing Mechanisms" proposed in the "Power Demand Side Management Measures (2023 Revised Edition)", the dynamic pricing model utilizes blockchain technology to establish a trusted trading platform. The design of user participation incentives requires balancing economic compensation with behavioral compliance. Empirical studies demonstrate that strategies integrating dynamic pricing with flexible load regulation can reduce system peak loads by 12–20% while decreasing the demand for energy storage frequency regulation capacity. This approach aligns with the policy orientation of "Load-Side Resources and Energy Storage Synergy" outlined in the "Notice on Further Promoting the Participation of New Energy Storage in Power Markets and Dispatch Operations" (2023) [8].

5. Case analysis and strategy validation

5.1. Typical application cases in microgrid scenarios

5.1.1. Configuration of energy storage system in industrial park microgrid

A coastal industrial park has deployed a 5MW/20MWh lithium iron phosphate (LFP) energy storage system featuring a dual-layer BMS architecture for real-time SOC/SOH monitoring (error ≤ ± 3%), with integrated liquid cooling thermal management technology (cell temperature variation < 1.5°C). By implementing a "low storage, high discharge" strategy for peak shaving arbitrage and combining variable speed generator (VSG) technology to provide inertia support (response time ≤ 200ms), the system reduces annual operating costs by 2.1 million yuan. With 82% renewable energy penetration and a carbon emission intensity of 0.32kgCO_2/kWh, it complies with the "Priority Dispatch" requirement under the "Management Specifications for New Energy Storage Projects (Trial)", demonstrating the economic-environmental synergistic benefits of energy storage in industrial applications.

5.1.2. Off-grid microgrid dispatching scheme for remote areas

A high-altitude off-grid system employs a "10MW wind power + 3MW/12MWh flow battery" architecture, achieving coordinated control of wind, solar, and storage through MPC algorithm. The system utilizes VSG technology to maintain frequency deviation ≤ 0.2Hz, with a black start strategy reducing fault recovery time to 45 seconds. Operational data shows renewable energy supply accounts for 93% of total power, diesel engine operation time decreases by 62%, and carbon emission intensity drops to 0.18kgCO_2/kWh. These metrics fully comply with the "Guidelines for Promoting Rural Energy Transition," demonstrating the off-grid system's power supply reliability and low-carbon benefits in extreme environments.

5.2. Simulation experiment and result analysis

5.2.1. Comparison of multi-objective optimization algorithms

Through industrial park microgrid case studies, the performance of PSO, NSGA-III, and DRL algorithms was compared. PSO converges quickly (50 iterations) but is prone to local optima, with a daily average cost of 87,000 yuan. NSGA-III demonstrates superior solution set distribution, reducing costs to 82,000 yuan, though with a 40% increase in computation time. DRL, based on the MADDPG framework, dynamically adapts to electricity price fluctuations, achieving optimal costs (79,000 yuan) and millisecond-level response. Experiments show DRL outperforms others in overall performance, though it requires high-performance computing platforms. Its carbon emission intensity (0.33 kg CO_2/kWh) is 24% lower than PSO, validating the technical requirements for adaptive optimization in the "14th Five-Year Plan" New Energy Storage Development Implementation Plan.

5.2.2. System performance metrics under different control strategies

Comparing with traditional scheduling, economic optimization, and multi-objective collaborative strategies, the traditional strategy incurs a daily operational cost of 95,000 yuan with a peak-valley difference rate of 1.8. Economic optimization (PSO) reduces costs to 87,000 yuan but increases the solar curtailment rate to 12%. The multi-objective strategy (DRL+NSGA-III) achieves a balanced optimization of 79,000 yuan in cost, 5% solar curtailment rate, and 0.33 kgCO_2/kWh carbon emission intensity, with frequency deviation stabilized within ± 0.1 Hz. The energy storage cycle efficiency improves to 93%, validating the feasibility of the "safety-economy-low-carbon" synergy as required by the Guidelines for Power System Security and Stability (2023).

5.3. Empirical research and technical challenges

5.3.1. Validation of actual operational data and deviation analysis

Based on annual operation data from industrial park microgrids, the multi-objective scheduling model's actual daily average cost reached 81,000 yuan, deviating 2.5% from the simulation's 79,000 yuan. This discrepancy primarily stems from wind/solar forecasting errors (RMSE 9.8%) and load fluctuations (7% of variance). The ±

0.12Hz frequency deviation marginally exceeded simulation values, caused by the BMS's SOC estimation error (± 3.5%) leading to delayed power response. Uneven thermal management reduced energy storage efficiency from 93% to 91.2%, with an annual degradation rate of 3.2%. The study reveals that dynamic carbon price fluctuations and 15-minute user response delays exacerbate economic deviations, necessitating enhanced digital twin prediction models to meet the requirements of the "Code for Performance Testing of Electrochemical Energy Storage Power Stations" (GB/T 36547-2023).

5.3.2. Technical bottlenecks in high-rate renewable energy integration

The high proportion of renewable energy (penetration rate > 80%) presents three core challenges for power systems as follows:

(1) Inertia deficiency: Existing lithium battery storage systems (response time ≥ 200ms) cannot meet second-level frequency regulation requirements;

(2) Inadequate wind/solar forecasting accuracy (short-term RMSE 12–15%), resulting in 20% redundant reserve capacity;

(3) Poor communication protocol compatibility among multi-source heterogeneous devices (e.g., low conversion efficiency between Modbus and IEC 61850), which limits the timeliness of coordinated control.

The New Power System Development Blue Book (2023) highlights the need to overcome challenges in wide-frequency-domain inertia support, digital twin forecasting, and cross-protocol communication technologies. Currently, long-duration energy storage technologies like flow batteries (cost > 3000 yuan/kWh) have yet to achieve economic breakthroughs [9,10].

6. Conclusion

This study validates the effectiveness of BMS high-precision monitoring and multi-objective optimization scheduling in smart microgrids, achieving an 18% reduction in operational costs and a 0.33 kgCO_2/kWh decrease in carbon emission intensity. Future efforts should focus on advancing AI-driven control, solid-state battery applications, and cross-microgrid coordination technologies to align with the "14th Five-Year Plan for New Energy Storage Development". These initiatives will drive cost reduction and efficiency improvements in long-duration energy storage solutions like flow batteries, supporting the zero-carbon goals of the new power system.

Disclosure statement

The author declares no conflict of interest.

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