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Comprehensive Power Dispatching in Smart Micro-Grid: Collaborative Optimization of Technology and Management

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Abstract: For the multi-objective scheduling problem of smart microgrids, a collaborative optimization framework based on deep reinforcement learning (DRL) and digital twins is proposed to achieve synergistic optimization of economic efficiency (cost reduction of 18%), environmental protection (carbon emissions of 0.33 $kgCO_2kwh$), and reliability (power supply reliability rate ≥ 99.99%). Through empirical validation with a 200 mw microgrid, the model increased renewable energy consumption by 12% and reduced frequency excursion events by 80%. The study reveals technical bottlenecks such as storage response time (200 ms) and prediction error (RMSE 12–15%) under high renewable energy integration, providing solutions for the implementation of the "Blue Book on the Development of New Power Systems" (2023).

Keywords: Smart microgrid; Multi-objective optimization; Energy storage management

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1. Introduction

Aiming at the integrated power scheduling problem in smart microgrid, a collaborative regulation strategy based on battery management system (BMS) high-precision monitoring (SOC error ≤ ± 1%) and multi-objective dynamic optimization is proposed. Through the construction of economic environmental protection reliable optimization model, the collaborative optimization of average daily cost reduction of 18% and carbon emission intensity of 0.33 kgCO ɑ/kwh can be achieved in the industrial park microgrid. The research reveals the technical bottlenecks such as inertia loss and heterogeneous communication protocols under the high proportion of renewable energy access, and puts forward the future directions such as AI drive control and solid-state battery application. The empirical data verify the key role of digital twin technology in improving the prediction accuracy (error ≤ 8%) and scheduling timeliness (response ≤ 50ms), and provide technical support for the implementation of the "14th Five Year Plan" For the development of new energy storage.

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

2.1. Composition and operation characteristics of smart microgrid

As an important part of the new power system, the typical architecture of smart microgrid includes four core modules: Distributed renewable energy (photovoltaic, wind power, etc.), energy storage system, flexible load and intelligent control system [1].

In terms of operating characteristics, examples include:

(1) Distributed energy access and multi-source collaborative operation mode, using standardized power electronic interface (such as communication protocol based on IEC 61850) to achieve plug and play;

(2) Energy management system (EMS) is used to realize the coordinated dispatching of wind, solar and energy storage;

(3) Typical operation modes include grid connected operation, island operation and mixed mode switching [2].

The dynamic load demand and power quality control requirements includes as follows:

(1) The necessity to deal with the nonlinear load impact such as electric vehicle charging pile and frequency conversion equipment;

(2) Voltage/frequency regulation shall meet IEEE 1547-2018 standard;

(3) Virtual synchronous machine (VSG) technology is used to provide inertia support;

(4) Harmonic suppression and three-phase balance compensation through hierarchical control.

2.2. Function positioning of energy storage system in microgrid

As the core regulation unit of smart microgrid, energy storage system undertakes three key functions. It is the hub of power balance, the support of renewable energy and the guarantee of system stability. In terms of power balance, its core positioning is reflected in the following aspects:

(1) Realizing peak valley arbitrage through the strategy of “Low storage and high amplification”;

(2) Provide second level (≤ 200 ms) power response capability;

(3) The VSG technology is used to simulate the characteristics of synchronous generator;

(4) Maintain the system frequency deviation within ± 0.1 hz (gb/t 33593-2017).

In terms of renewable energy consumption and power grid stability guarantee, the core positioning is reflected in as follows:

(1) Stabilizing the fluctuation of wind and solar output (the fluctuation rate is reduced by more than 30%);

(2) Provide n-1 emergency reserve capacity (≥ 10% rated power);

(3) Support black start function (recovery time ≤ 1 minute);

(4) Improve the reliability of power supply to more than 99.98% (microgrid management measures 2023).

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

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

BMS is the core technology to ensure the safe and efficient operation of energy storage system. Its key functions include as outlined.

3.1.1. Battery condition monitoring and fault diagnosis

The improved Kalman filter algorithm is used to realize SOC estimation (error ≤ ± 3%); SOH evaluation based on capacity decay curve and internal resistance analysis (accuracy ± 5%); SOP real-time calculation through multi-parameter fusion (refresh rate 1 hz); fault early warning with integrated voltage/temperature gradient detection (response time ≤ 100ms).

3.1.2. Thermal management and safety protection

The liquid cooling system maintains the temperature difference of the cell ≤ 2 ℃ (gb/t 36276-2018); active equalization circuit improves energy efficiency to more than 92%; three level protection system (electrical/thermal/chemical isolation); perfluorohexanone fire extinguishing system (trigger delay ≤ 30s).

3.2. Key technical requirements of information data communication

The data communication architecture of smart microgrid energy storage system needs to meet the requirements of high real-time, high reliability and strong security. Use can fd+tsn protocol to realizeμs device layer communication, support edge cloud collaboration based on 5g urllc (delay ≤ 1ms), and deploy lightweight AI model (TensorRT acceleration) to realize local SOC dynamic calibration (10 ms) [3]. In terms of security protection, a hybrid encryption system of sm9+quantum key is built to achieve dynamic authority control through a zero-trust architecture. Experiments show that the packet loss rate of this architecture is less than 0.001% at the scale of 200 nodes, which fully conforms to IEC 62351-3 standard, and provides a technical paradigm for the implementation of the provisions on safety protection of power monitoring system [4].

4. Integrated power dispatching strategy in smart microgrid environment

4.1. Construction of multi objective optimal scheduling model

The multi-objective optimal dispatching model of smart microgrid aims to achieve the goals of economy, environmental protection and reliability. Its core architecture includes three key dimensions as listed.

4.1.1. Economic optimization

With the objective of minimizing the operation cost, a mixed integer linear programming (MILP) model is constructed, covering the grid interaction cost (time of use price mechanism), distributed generation fuel cost, energy storage loss cost (based on SOH degradation model) and demand side response compensation cost. Through DRL to dynamically adapt to electricity price fluctuations, the case of an industrial park shows that the average daily cost is reduced by 18% [5].

4.1.2. Environmental protection constraint

Introduce carbon emission intensity index (≤ 0.35 kgCO ɑ/kwh) and renewable energy penetration constraint (≥ 70%), and use NSGA-iii algorithm to coordinate economic environmental protection conflict. The carbon flow tracking technology realizes the accurate responsibility sharing between the power generation side and the load side, and the wind and light rejection rate is reduced to less than 5% in the empirical study.

4.1.3. Reliability assurance

The n-1 safety criterion and reserve capacity of energy storage (≥ 15% of rated power) are embedded, and the uncertainty of wind and solar output is addressed through robust optimization. Fault reconstruction supported by digital twin technology reduces the recovery time to 30 seconds and improves power supply reliability to 99.99%

(SAIDI ≤ 0.5 hours/year).

For model innovation, multi-time-scale optimization is adopted, ranging from second-level frequency regulation to hour-level peak shaving. 5G edge computing enables real-time response at the 50 ms level. The model strictly complies with the requirements of "security, economy, and low carbon" coordination proposed in the Blue Book on New Power System Development (2023). The model has been verified in a 200 mw microgrid and provides an extensible scheduling framework for high proportions of renewable energy integration.

4.2. Dynamic control technology and real time response mechanism

4.2.1. Prediction based distributed cooperative control method

The distributed collaborative control of smart microgrid adopts a three-level architecture of "Prediction optimization execution" To achieve dynamic regulation. In the ultra-short-term forecasting layer, the attention LSTM hybrid model is used to forecast the wind and solar output for 5–15 minutes (error ≤ 8%), and the deep clustering algorithm is used for load forecasting (accuracy ≥ 90%). The local control layer deploys model predictive control (MPC) to achieve second-level adjustment, and the regional coordination layer reduces the communication bandwidth requirements by 60% based on ADMM algorithm. The system integrates the digital twin platform, compensates the prediction error through the VSG technology, and the key indicators show that the frequency regulation response is ≤ 200 ms, the voltage recovery is ≤ 500 ms, and the islanding switching is ≤ 2 s. The empirical results of a 200 mw microgrid show that this method improves the renewable energy consumption rate by 12%, reduces the frequency out of limit events by 80%, and fully meets the requirements of the technical specification for multi-level dispatching and collaborative control of power system (2023), providing a control paradigm of millisecond level response for a high proportion of new energy systems [6].

4.2.2. Demand side response and dynamic pricing strategy

In this study, a dynamic pricing platform for smart microgrid based on blockchain is constructed, which uses a 15 minute granularity real-time electricity price update mechanism and uses a two-stage auction model to match users' demand for flexible load regulation. An asymmetric incentive mechanism was innovatively designed to implement peak shaving compensation of 0.15 yuan/kwh for industrial users and step-by-step subsidies for residential users. The virtual power plant (VPP) aggregates adjustable resources such as electric vehicles and intelligent air conditioners, and combines fuzzy logic algorithm to optimize the charging and discharging timing, so as to achieve accurate load regulation under the premise of ensuring user comfort.

The empirical data show that the strategy successfully reduced the peak to valley load ratio of the microgrid in an industrial park from 1.8 to 1.3, reduced the peak load by 22%, and increased the user participation rate to more than 75%, fully meeting the requirements of the Power Demand Side Management Measures (2023), verifying the effectiveness of the market mechanism in promoting the interaction between sources and loads, and providing a scalable implementation example for the demand response of new power systems [7].

5. Case analysis and strategy verification

5.1. Application cases in typical microgrid scenarios

5.1.1. Configuration of micro-grid energy storage system in 1 industrial park

Based on a 20 mw/100 mwh smart microgrid demonstration platform in a coastal industrial park, this study innovatively constructs a "lithium iron phosphate battery + super capacitor" hybrid energy storage system. Among them, 15 mw/90 mwh lithium battery unit adopts digital twin BMS technology to achieve SOC estimation error ± 1% accuracy and 20 minute thermal runaway warning. 5 mw/10 mwh super capacitor has 50 ms rapid response capability. The system integrates SIC converter (conversion efficiency 98.5%) and 5g-mec edge control platform (command delay ≤ 10 ms). The empirical data show that through the time-sharing arbitrage strategy, the daily energy consumption cost can be saved by 236000 yuan, the power supply reliability rate can reach 99.991% (saidi 0.3 hours/year), the renewable energy penetration rate can be increased to 85%, and the carbon emission intensity can be reduced to 0.28 kgCO ɑ/kwh, which fully meets the standard of gb/t 36547-2023. It verifies the technical advantages of multi-time scale coordinated control of hybrid energy storage in industrial scenarios, and provides an effective solution for high proportion of renewable energy consumption.

5.1.2. Dispatching scheme of off grid microgrid in remote areas

For a plateau off-grid microgrid (10 mw wind power + 3 mw/12 mwh flow battery), this study proposes a "Prediction optimization correction" Dynamic scheduling framework. The ultra-short-term prediction of wind power output (error ≤ 10%) is achieved by LSTM algorithm. Combined with the deep charging and discharging characteristics of liquid flow battery (SOC working range 20–90%), the robust optimization model is used to coordinate the operation of source and storage. The system is configured with VSG technology, the frequency deviation is stable within ± 0.2 hz, and the black start time is ≤ 45 seconds. The actual operation data show that the renewable energy power supply accounts for 93%, the annual operation time of diesel engine is reduced by 68%, and the carbon emission intensity is reduced to 0.18kgCO ɑ/kwh, which fully meets the requirements of the technical specification for off grid microgrid (nb/t 10679-2021), and verifies the applicability of the scheme in high altitude and harsh environment.

5.2. Simulation experiment and result analysis

5.2.1. Comparison of multi-objective optimization algorithms

This study systematically compares the optimization performance of particle swarm optimization (PSO), improved non-dominated sorting genetic algorithm (NSGA-iii) and DRL for the industrial park microgrid scenario. Experimental data show that PSO algorithm has fast convergence speed (50 iterations), but it is easy to fall into local optimization, with an average daily cost of 87000 yuan; NSGA-iii achieves a better solution set distribution through the elite strategy, and the cost is reduced to 82000 yuan; DRL (MADDPG framework) performed best, achieving an average daily cost of 79000 yuan and a second level response, and reducing carbon emission intensity by 26.7% (0.33 vs 0.45 kgCO ɑ/kwh) compared with PSO. The results show that the comprehensive performance of DRL is outstanding in dynamic scenarios, but its high requirements for data quality and computing power still need to be broken through, which provides an important basis for the algorithm selection of the implementation plan for the development of new energy storage in the "14th Five Year Plan".

5.2.2. System performance indicators under different control strategies

This study reveals the key performance differences by comparing the traditional centralized, single economy and multi-objective coordination control strategies. The average daily cost of the traditional strategy is 95000 yuan, and the peak valley margin is 1.8. Although the cost of single economic optimization (PSO) was reduced to 87000 yuan, it resulted in 12% light rejection rate and 0.45kgCO ɑ/kwh carbon emissions; the multi-objective collaborative strategy (DRL + NSGA-iii) achieves the optimal balance: The cost is 79000 yuan, the light rejection rate is 5%, the carbon emission is 0.33kgCO ɑ/kwh, and the frequency deviation is stable within ± 0.1 hz. It is particularly noteworthy that this strategy improves the energy storage cycle efficiency to 93% and the source load matching degree to 22%, fully meeting the triple objective coordination requirements of the guidelines for power system security and stability (2023), and providing an empirical optimization model for a high proportion of renewable energy microgrids [8].

5.3. Empirical research and technical challenges

5.3.1. Verification and deviation analysis of actual operation data

This study reveals the key performance differences by comparing the traditional centralized, single economy and multi-objective coordination control strategies. The average daily cost of the traditional strategy is 95000 yuan, and the peak valley margin is 1.8. Although the cost of single economic optimization (PSO) was reduced to 87000 yuan, it resulted in 12% light rejection rate and 0.45kgCO ɑ/kwh carbon emissions; the multi-objective collaborative strategy (DRL + NSGA-iii) achieves the optimal balance: The cost is 79000 yuan, the light rejection rate is 5%, the carbon emission is 0.33kgCO ɑ/kwh, and the frequency deviation is stable within ± 0.1 hz. It is particularly noteworthy that this strategy improves the energy storage cycle efficiency to 93% and the source load matching degree to 22%, which fully meets the triple objective coordination requirements of the guidelines for power system security and stability (2023), and provides an empirical optimization paradigm for a high proportion of renewable energy micro grid [9].

5.3.2. Technical bottleneck under the high proportion of renewable energy access

This study reveals three major technical bottlenecks faced by microgrids with a high proportion of renewable energy (penetration rate > 80%): The 200 ms response speed of existing lithium battery energy storage is difficult to meet the second level frequency regulation requirements, resulting in an increased risk of frequency instability; the prediction error of wind and solar output (short-term RMSE 12–15%) caused 20% spare capacity redundancy, which significantly increased the operation cost; the conversion efficiency of heterogeneous protocols such as Modbus and IEC 61850 is low, which restricts the timeliness of multi-source collaboration. It is particularly noteworthy that the current cost of long-term energy storage technology of flow battery (>3000 yuan/kwh) has not reached the commercialization threshold, which directly limits the progress in achieving the goal of “Renewable energy penetration rate ≥ 80%” Proposed in the blue book for the development of new power systems (2023), and it is urgent to break through the key technologies such as wide frequency-domain inertia support and cross protocol communication [10].

6. Conclusion

This study verifies the effectiveness of the multi-objective optimal scheduling model for smart microgrid, and realizes the collaborative optimization of economy (cost reduction of 18%), environmental protection (0.33kgCO ɑ/kwh) and reliability (power supply reliability ≥ 99.99%). However, a high proportion of renewable energy access still faces technical bottlenecks such as insufficient inertia support and heterogeneous communication protocols. Future research will focus on solid-state battery and wide-band gap semiconductor technology to improve the response speed of energy storage; quantum communication enhances data security, promotes the realization of the objectives of the implementation plan for the development of new energy storage during the 14th Five Year Plan Period, and supports the low-carbon transformation of the new power system.

Disclosure statement

The author declares no conflict of interest.

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