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Review on Source-storage Coordinated Optimization Operation and Control Considering New Energy Uncertainty

Dingyu Hao

School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou, China
19703310807@163.com

Abstract. With the increasing proportion of renewable energy sources, the output characteristics of wind and solar power in power systems have become increasingly stochastic. This phenomenon not only affects clean energy utilization efficiency but also poses significant challenges to the safety and stability of traditional power grids. In these conditions, energy storage devices have become essential for reducing power fluctuations from renewable sources, and they are crucial for source-storage joint dispatching and dynamic control. Through literature review and comprehensive analysis, this study investigates characterization methods and quantification approaches for renewable energy uncertainty within source-storage coordination frameworks, explores optimization model design philosophies and related strategies, and evaluates current mainstream control technology trends. The uncertainty assessment system, established using parameters such as prediction deviations and fluctuation amplitudes, demonstrates greater scientific rigor than conventional coarse scenario segmentation methods. Multi-objective function-based collaborative planning approaches are gradually replacing single-objective modeling paradigms. Regarding real-time response performance improvement techniques, model predictive control (MPC) integrated with reinforcement learning algorithms has become a new research focus. This study aims to clarify academic frameworks in relevant fields and provide theoretical foundations and technical support for practical applications of source-storage coordination mechanisms in high-renewable-energy environments.

Keywords: New energy, Uncertainty, Source-storage coordination, Optimization operation, Optimization control

1. Introduction

Renewable energy sources like wind and solar power are becoming more and more attractive as feasible substitutes for conventional energy systems against the backdrop of the world's deepening green and low-carbon transition and continuous progress toward the "dual carbon" goals. Future power grid development will be defined by their increasing penetration rates and grid integration capabilities. However, the inherent instability of renewable energy generation- characterized by randomness, volatility, and intermittency-poses significant challenges to power system stability. These characteristics not only lead to abnormal grid frequency fluctuations and voltage instability

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but also complicate dispatch control processes. The worsening issue of wind and solar curtailment further reduces the overall capacity for renewable energy integration, ultimately impacting the economic efficiency of power grids.

The academic community worldwide has conducted extensive research on uncertainties in renewable energy systems across multiple dimensions. Researchers employ precise modeling techniques and quantitative methods to analyze fluctuation characteristics of renewable energy sources within source-storage systems. From an uncertainty perspective, they develop coordinated optimization scheduling strategies and refine efficient coordination control technologies tailored to specific scenarios. However, current studies still face challenges in adapting to extreme operating conditions, implementing integrated regulatory strategies across time scales, and translating theoretical findings into practical applications. These areas require continuous refinement and advancement.

This paper explores academic advancements in source-storage coordinated optimization under high renewable energy penetration, focusing on key research areas such as uncertainty quantification frameworks, collaborative mechanism development, and optimization algorithm enhancements. By integrating bibliometric analysis, case studies, and comparative research methodologies, we systematically summarize theoretical breakthroughs and practical innovations in recent years. Through critical examination of existing research findings, we identify current research limitations and propose future research directions, thereby providing theoretical foundations and technical references for technological innovation and engineering applications of source-storage coordinated control systems in next-generation power grids.

2. Uncertainty management and adaptation logic for source-storage synergy in new energy systems

Within the framework of source-storage coordinated optimization, accurate analysis of renewable energy uncertainties is crucial. These uncertainties primarily stem from discrepancies between actual and predicted generation from renewable sources such as wind and solar power. Such variations are determined by the inherent unpredictability of meteorological conditions, exhibiting pronounced temporal diversity and stochastic characteristics, alongside strong system coupling [1]. Compared to standalone renewable energy installations, uncertainties in source-storage-integrated systems directly affect generation efficiency. Moreover, interactions among energy storage devices can have complex and far-reaching effects on system stability, economic performance, and safety [2].

The academic community has proposed numerous quantitative evaluation methods and visualization techniques to characterize uncertainty in optimization models. From a quantitative perspective, commonly used key statistics include prediction error metrics (MAPE, RMSE) and volatility-related parameters that describe volatility levels, with confidence intervals that explain the morphology of uncertainty distributions [3]. Regarding representation methods, current approaches can be categorized into four major types: 1) Constructing multidimensional stochastic scenarios using probability distributions to describe complex system uncertainty distributions (e.g., generating wind power or load power probability scenarios through Latin hypercube sampling); 2) Solving global optimal strategies under extreme conditions based on robust theory, which demonstrates advantages in highly unpredictable scenarios; 3) Distributed robust optimization that achieves further improvements (e.g., Zhang et al. [4] proposed a novel hybrid framework incorporating Wasserstein distance and moment estimation for campus integrated energy management, proving superior efficiency compared to traditional robust programming); 4) Opportunity constrained programming that allows decision objectives to tolerate non-compliance within tolerance thresholds,

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achieving dynamic balance between risk control and cost-effectiveness. Chai's team addressed coupled uncertainties in wind power, photovoltaic systems, and user behavior for virtual power generation units by applying fuzzy-logic-based opportunity-constrained modeling, transforming the original problem into a solvable classical mathematical model [5].

Table 1. Comparison of representation methods for new energy uncertainty

Representation Method	merit	shortcoming	applicable scene
Scenario Analysis Method	The model is intuitive and can generate rich future possibilities	Computational complexity increases exponentially with the number of scenarios	Scenarios with known probability distributions, such as daily planning
robust optimization	The results are reliable and withstand the most extreme scenarios.	The results were overly conservative with poor economic feasibility.	Scenarios with extremely high security requirements, such as backup configurations
distributed robust optimization	Balancing Robustness and Economic Efficiency	Model construction and solution are relatively complex	Scenarios with limited historical data and requirements for cost-effectiveness
chance constrained programming	Achieving a balance between economy and reliability	The selection of confidence levels depends on empirical evidence	Scenarios that allow for certain risks in exchange for economic viability

The instability of renewable energy has become a major challenge for source-storage coordinated regulation systems, with its impacts across all power system components arising from these integrated control mechanisms [6]. The aforementioned diagrams demonstrate characterization methods for renewable energy uncertainty that can be applied in specific operational contexts. Zhang Junhua et al. argue that traditional frequency-response analysis methods fail to adequately capture dynamic characteristics under high levels of renewable energy integration. Due to the stochastic and intermittent nature of renewable generation, this leads to active power supply-demand imbalances and intensified frequency fluctuations [6]. From an operational economics perspective, uncertainty increases the risk of wind and solar curtailment and elevates maintenance costs due to frequent energy storage charging/discharging operations [5]. Particularly in dispatch decision-making processes, traditional single-phase static programming approaches prove inadequate given uncertainties on both supply and demand sides. Multi-time-rolling optimization methods are now essential to enhance emergency response capabilities [3].

The core of source-storage coordination mechanisms lies in leveraging the dynamic regulation capabilities of energy storage systems to compensate for the unpredictable fluctuations in renewable energy output. When actual renewable power generation exceeds projected levels, storage devices absorb excess electricity through charging and discharging. Conversely, if actual generation falls below forecasts, stored energy is immediately released to balance supply and demand [7]. Essentially, this approach utilizes controllable energy storage to mitigate output instability from new energy sources. Existing research indicates that traditional energy storage control methods based on scheduled operations are evolving toward intelligent, integrated systems that ultimately achieve globally optimal design solutions. In order to improve wind power frequency response performance, researchers, including Yao [7], presented a source-storage joint dispatching approach that incorporates energy storage component state information during turbine operation to switch from passive response to active grid stabilisation. Meanwhile, Hu et al. [8] developed an uncertainty-based source-storage collaborative planning framework for active distribution networks, optimizing

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energy storage deployment to improve clean energy integration capacity while significantly enhancing grid security.

3. Construction framework for source-storage coordinated optimization operation model

Transforming uncertainty management into precise mathematical formulations constitutes a critical component of source-storage coordinated dispatch optimization research. The theoretical framework primarily encompasses three key aspects: objective function formulation, constraint condition extraction, and modeling methodologies based on stochastic characteristics [9]. The objective function serves as a fundamental basis for regulation optimization processes, reflecting the primary operational objectives of power systems. Existing studies predominantly adopt single-objective approaches-such as cost minimization, renewable energy integration enhancement, or grid energy consumption reduction-in typical application scenarios, without considering environmental complexity and variability, and often adhere to simplistic assumptions. Consequently, multi-objective optimization has gradually replaced traditional one-dimensional objective frameworks, emerging as a focal point in both academic and industrial research domains.

Multi-objective optimization problems generally fall into three categories: (1)Economic-environmental coordination models, exemplified by the virtual power plant dispatching model proposed by Chai et al. [5], which aims to minimize both operational costs and carbon emission trading expenses; (2) Economic-security synergy models, such as those studied by Hu et al. [8] focusing on enhancing renewable energy integration efficiency while ensuring grid stability; (3) Multi-stakeholder collaborative models, like the source-storage integrated transmission research conducted by Tang et al. [9], designed to maximize overall economic benefits through coordinated resource allocation. Constraints are essential for defining the feasible solution space and ensuring practical outcomes. Typical source-storage coordination frameworks incorporate four key constraints: operational constraints (including output limits for renewable units, regulation rates, energy storage capacity, state-of-charging conditions, conversion efficiency, and capacity specifications); energy balance conditions (real-time dynamic matching between generation facilities, storage systems, and load demands); grid security regulations (including voltage limits for distribution networks and main grids, along with transmission flow distribution parameters); and market compliance rules (adherence to spot market mechanisms or cross-regional agreements regarding bidding protocols and settlement procedures) [2].

To incorporate uncertainty factors into source-storage collaborative optimization models, it is essential to develop mathematical models that combine flexibility with adaptability. Mainstream modeling techniques employ diverse approaches to express uncertainties: stochastic programming models base their analysis on scenario-based frameworks, addressing uncertainty variables through deterministic objective functions across multiple scenarios, while achieving risk control via scenario generation and weight allocation – as explored in Xu et al. 's research [3]. Robust optimization and distributed robust optimization leverage fuzzy set theory or probabilistic methods to identify robust decision-making strategies under extreme conditions, as demonstrated by Zhang Xiaolin's team [4], which applied distributed robust optimization to develop high-confidence strategies for complex systems. Opportunity-constrained programming uses probabilistic opportunity-constraint functions to ensure decision objectives remain within specified confidence intervals. The selection of methodologies requires a comprehensive evaluation based on specific problem characteristics and technical requirements.

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4. Source-storage coordinated optimization control methods and development trends

The optimized operational model establishes a strategic guidance framework for the system, while refined control methods focus on executing specific tasks and adapting to dynamic environmental changes. Key technologies in real-time or near-real-time control include model predictive control (MPC), reinforcement learning (RL), and traditional rule-based control—each distinct yet widely adopted. Model predictive control (MPC), a hallmark advanced strategy, integrates rolling optimization decisions with closed-loop correction mechanisms. In wind-storage hybrid frequency regulation systems, Yao et al.'s adaptive MPC technique uses frequency variation rate as a major parameter to control power output [7]. By applying rolling optimization principles, this method incorporates real-time predictive data into control commands during each iteration, effectively mitigating short-term power fluctuations caused by external disturbances in renewable energy systems.

As a data-driven control approach that eliminates the need for precise mathematical modeling, reinforcement learning (RL) offers significant advantages for coordinated dispatching of microgrid source-storage systems, particularly in complex scenarios with non-convex nonlinear constraints. The reinforcement learning algorithm proposed by Liu Linpeng et al. [10], which integrates offline deep neural network training with online decision-making mechanisms, effectively enhances real-time system response performance while improving adaptability to diverse environmental conditions. This makes it highly suitable for tasks requiring global optimization objectives. In contrast, traditional rule-based control strategies rely on predefined thresholds and logical rules for decision-making, exhibit low efficiency when encountering sudden operational conditions or scenarios beyond predefined rules, and often struggle to achieve global optimal solutions.

To address the inherent limitations of single algorithms, researchers have proposed various improvement measures. Yao et al. [7] used output conversion features and dynamically adjusted weight coefficients to automatically tune the parameters of an MPC controller. This made it possible to use adaptive control methods when the system's operating conditions change. Meanwhile, Liu's team [10] developed an autonomous approach to generating safety policies leveraging partial prior models. By utilizing neural networks to create virtual simulation environments that replicate real-world grid scenarios, this solution significantly accelerates data acquisition while ensuring decision-making processes comply with power system safety standards.

The overarching development trends in source-storage collaborative optimization control technology emphasize interdisciplinary integration and advanced intelligence. Three primary research directions have emerged [3]: First, combining Model Predictive Control (MPC) with Reinforcement Learning (RL) to achieve model-guided precision control and experience-driven dynamic adaptation [4]. Second, establishing data-driven analytical frameworks that leverage deep neural networks for high-precision short-term forecasting of renewable energy generation [5], with the resulting predictions incorporated into closed-loop control systems to enhance decision-making predictability and accuracy. Third, designing multi-agent collaborative mechanisms for complex environments. Leveraging the characteristics of large-scale distributed energy systems [6], research focuses on reinforcement learning-based swarm-based interactive scheduling solutions to meet the requirements of modern grid distributed architectures.

5. Conclusion

This study primarily examines source-storage coordinated optimisation scheduling in the context of renewable energy uncertainties. From a comprehensive standpoint, it offers a methodical review and

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examination of these scheduling strategies, accompanied by in-depth introductions to advanced technologies in this domain. From the established argumentative framework, the following essential conclusions can be derived:

The quantitative analysis of renewable energy uncertainties under source-storage coordination scenarios has evolved from single-scenario approaches to a refined research paradigm employing distributed robust optimization and opportunity constraints. These uncertainties significantly impact power system frequency stability, economic operation, and dispatching decisions. The core mechanism of source-storage coordination relies on the regulation capabilities of energy storage devices to counteract the stochastic nature of renewable energy output.

The research paradigm for source-storage coordinated optimization operation models is progressively evolving into a comprehensive framework centered on multi-objective optimization. This system primarily aims to reduce costs, increase energy integration rates, and improve system stability, achieving global optimization through constraints on equipment performance, grid architecture, and market mechanisms. Technical approaches such as stochastic programming, robust optimization, distributed robust methods, and chance-constraint programming each possess distinct characteristics, making multi-objective optimization modeling a focal point and a hot topic in current research. Current source-storage coordinated optimisation control research focuses on Model Predictive Control (MPC) and Reinforcement Learning. Time-domain optimisation makes MPC adaptable to complicated, dynamic circumstances, while RL is known for efficient learning in high-dimensional, nonlinear systems.

Existing research has made progress, but many issues remain. Analysing system uncertainties under extreme conditions, applying model engineering, and improving multi-time-scale collaborative regulation methods are still lacking. Next research should refine modelling techniques for stochastic fluctuations of renewable energy sources, improve multi-objective optimisation strategies, and develop intelligent control algorithms with robustness, cost-effectiveness, and self-learning capabilities.

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