Optimization of Wind-Solar-Energy Storage Scheduling in Smart Grids

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Abstract. The theme of this paper is the optimization scheduling of wind-solar-energy storage systems in relation to smart grids. It is a systematic study of the intermittency and uncertainty of wind and solar power generation, the bottlenecks in the functioning of the energy storage system, and the problem of multi-time-scale coordination. A multi-stage system of dispatch, incorporating forecasting, real-time rolling, and efficient optimization, is suggested, along with a multi-objective optimization model that balances economy, reliability, and environmental friendliness. The paper also discusses how the practice of dispatching is affected by various restraints, such as power equilibrium, equipment maintenance, the duration of energy storage, and the safety of power lines. It notes that in the future, there is a need to have recourse to such technologies as deep reinforcement learning and digital twins and to operate with flexible market mechanisms and carbon trading policies, to facilitate the efficient, safe and low-carbon functioning of wind-solar-energy storage systems, which gives the provisions of theories and applicable paths towards the creation of new power systems. Essentially, the optimum dispatch of wind-solar-energy storage systems requires additional enhancements in the study of wind-solar-energy storage forecasting technologies, the development of better mechanisms for multi-time-scale coordination, market exploration, interdisciplinary improvement, and the consistent innovation and perfection of wind-solar-energy storage optimization scheduling mechanisms.

Keywords: Smart grid; wind-solar-energy storage; renewable energy; optimal dispatch; energy storage system.

1. Introduction

A smart grid is a developed power infrastructure that incorporates current information and communication technology. The smart grid is more reliable, flexible, and cost-efficient than the traditional grid, and is able to adapt to the ever-changing relationship between power supply and demand. Smart grids rely on advanced communication networks and sensors to gather valuable information regarding the production of distributed energy resources, energy consumption patterns, and the behavior of electric vehicle users [1].

Nevertheless, despite the integrated wind-solar energy storage system's bright prospects, it presents several challenges in its application. To begin with, wind and solar power generation are subject to inherent intermittency and uncertainty, making them difficult to predict. Photovoltaic generation has been particularly affected by sun irradiance, cloud cover, and temperature, which tend to cause significant short-term fluctuations. The following characteristics pose a threat to the secure and stable functioning of the power grid, necessitating a greater reserve capacity and more complex dispatch strategies [2]. This concern has been brought to the forefront as the rate of renewable energy penetration continues to soar. Consequently, the immediate necessity is the employment of meteorological data, historical data, and artificial intelligence forecasting methods to enhance the predictability and the controllability of the wind and solar power generation [3]. Technical barriers also pose a challenge to the optimum functioning of the energy storage systems. Massive battery energy storage is costly to install and has a short lifespan; the charge and discharge process also accelerates deterioration, impacting the economic feasibility of the system [4]. Traditional linear dispatch models fail to consider the nonlinear properties of batteries, which depend on other factors such as temperature and state of charge, resulting in variations between the model and reality.

Moreover, there is a dilemma in configuring energy storage capacity: a larger capacity increases costs, while a smaller capacity fails to meet dispatch requirements [5]. To address these issues, researchers have proposed optimization models that consider the coupling of battery thermal and aging effects [4]. Hybrid energy storage systems (such as the combination of batteries and supercapacitors) have also been widely studied to overcome the limitations of single energy storage technologies.

Based on previous research, this paper proposes a "day-ahead - intraday - real-time" multi-stage rolling dispatch framework. The day-ahead level utilizes scenario-based stochastic programming based on LSTM prediction. The intraday level introduces model predictive control for 15-minute rolling corrections. The real-time level completes 5-minute ultra-short-term decision-making with a convex optimization model transformed by second-order cone conversion, achieving multi-time-scale power-energy coordination. Secondly, a multi-objective optimization model considering the coupling of battery electro-thermal and aging, carbon trading costs, and ancillary service revenues is constructed. The aging loss is explicitly quantified as a dispatch cost to achieve simultaneous optimization of economy and reliability. Finally, in response to the dual uncertainties of wind and solar power output and electricity prices, interval-scenario hybrid robust optimization is employed. Interval numbers are used to describe extreme fluctuations, while scenario trees are used to depict conventional randomness. A centralized-distributed energy storage coordination mechanism based on a two-stage game is designed to enhance the robustness and feasibility of the solution.

2. Optimization Strategies and Methods for Wind-Solar-Energy Storage Scheduling

2.1. Day-Ahead Forecast-Driven Optimization Schedule

Day-ahead optimization scheduling is a crucial component in the operation of wind-solar energy storage systems. Its objective is to submit rational generation and energy storage plans in the day-ahead market to ensure the safety and economic efficiency of the system. In this process, it is usually necessary to comprehensively consider the output forecast results of wind power and photovoltaic power, as well as multiple pieces of information such as load demand and electricity price levels. Forecasting accuracy significantly influences scheduling outcomes. Long short-term memory networks have become the mainstream choice because of their advantages in capturing the nonlinear characteristics of time series, which enables them to effectively deal with the volatility and correlation of wind and solar power output.

In specific scheduling modeling, the day-ahead optimization problem often aims to minimize the total system operating cost or maximize economic benefits as the objective function. The upper and lower limit of unit output, power balance constraints of the power grid, line flow constraints, and charging and discharging rate and capacity constraints of the energy storage system, etc. [6]. Due to the large uncertainty of wind and solar power, if based solely on one of the forecast results, the plan often deviates significantly from actual operation. To achieve more reasonable scheduling plans, many researchers employ scenario-based methods or interval optimization methods. Day-ahead scheduling is not only a technical problem, but also affected by the mechanism of market mechanism. In recent years, some scholars have also attempted to utilize this framework to integrate centralized and distributed scheduling. Through multi-level optimization, scheduling efficiency and flexibility are enhanced, resulting in overall benefits in a complex market [7].

2.2. Real-time Rolling Optimization Scheduling Strategy

Although day-ahead scheduling can provide an overall framework for system operation, dynamic adjustments are still necessary during real-time operation due to the errors in wind and solar forecasts and the stochastic fluctuations of resources. Real-time rolling optimization scheduling is proposed in this context. Its core idea is to periodically update the scheduling plan based on real-time monitoring and short-term forecasting results, ensuring the balance and economic efficiency of the power grid

[8]. In terms of specific methods, model predictive control is a widely used real-time scheduling tool. It can predict the system state over a future time horizon in each scheduling cycle and determine the optimal control decisions based on the rolling optimization concept, thereby achieving closed-loop operation of prediction, optimization, and execution [9]. Moreover, to meet the high computational efficiency requirements of real-time scheduling, many studies have transformed the original nonlinear problems into more solvable forms by employing convex optimization methods such as mixed-integer linear programming or second-order cone programming [10]. Practice has shown that a two-stage or multi-stage coordinated approach, combining day-ahead optimization and real-time rolling scheduling, can significantly improve the economic operation and power supply reliability of wind-solar-energy storage systems [8].

2.3. Multi-time-scale Coordinated Optimization Method

The operation of wind-solar energy storage systems involves multiple time scales: day-ahead, intra-day, and real-time, with different focuses at each stage. The day-ahead stage typically focuses on economic objectives, formulating long-term generation and energy storage strategies. The intra-day rolling stage adjusts plans on a shorter timescale to minimize the curtailment of wind and solar power and track the day-ahead plan. The real-time control stage emphasizes rapid response and stable operation [11]. Achieving coordination among these time scales has become a key issue in improving the overall performance of the system.

Multi-time-scale coordination frameworks have been the subject of discussion in the past several years. For example, one typical approach is to perform the energy dispatch task on a long timescale with centralized energy storage and the rapid power balance task on a short timescale with distributed energy storage, thereby leveraging the merits of various energy storage types [8]. The second type of approach is the so-called generalized energy storage services, which encompass subdivisions of energy storage such as electric vehicles, hydrogen storage, and demand response resources. These are optimized in a coordinated fashion across various time scales to achieve flexibility in dispatch across systems [12]. These methods of multi-time-scale, multi-coordinated optimization not only mitigate the effects of renewable energy production uncertainty but also offer a viable avenue for the future evolution of the smart grid paradigm [12].

2.4. Robust Optimization Methods Considering Uncertainty

The main challenges of power grid dispatching include the uncertainty and variability of wind and solar power generation. Additionally, as illustrated in Figure 2, there are significant variations and errors in the forecasted production of photovoltaic and wind power at both the sending and receiving end locations, which explains the need to adopt robust optimization. In response, extensive research has been conducted on the use of robust optimization techniques to enhance the stability and reliability of dispatching strategies. The interval number method represents the uncertainty of wind and solar power generation as interval numbers, constructs an interval optimization model, and transforms the problem into a deterministic optimization model for solution using order relations and possibility theory, thereby obtaining a dispatching plan that is adaptable to various uncertain scenarios.

The other type of approach is the scenario-based approach, which involves creating a series of representative wind and solar power generation scenarios. In this case, a final optimal strategy is achieved by optimizing the dispatch plans. Researchers have also proposed a two-stage optimization model that utilizes game theory in the context of multiple stakeholders. This framework serves as a coordinator for the day-ahead and intra-day functionality of centralized and distributed energy storage, aiming to enhance overall system gains [8].

The theory of information gap decision has become increasingly relevant in addressing uncertainty in electricity prices and demand for load. Its strength lies in the ability to equalize the risk-averse and risk-seeking operational strategies, and adjust the dispatch plans accordingly to accommodate the variety of market conditions [13]. Sound optimization algorithms offer solutions for wind-solar energy storage systems, enabling them to overcome uncertainty and become more stable and economical, even in extreme situations.

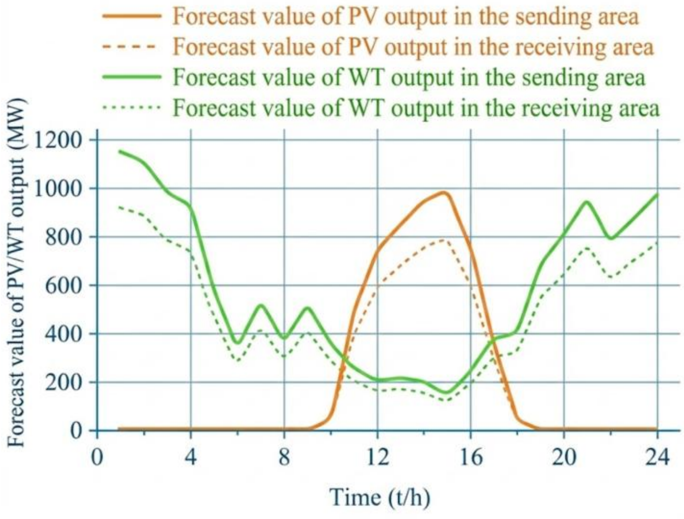

Fig. 1 Forecast value of PV/WT output in the sending and receiving areas[13]

3. Optimization Scheduling Model

3.1. Objective Function Design

3.1.1 Economic objectives

Economic efficiency is a key objective in optimizing wind-solar energy storage scheduling. Its essence is to seek cost minimization or profit maximization through rational dispatch strategies under different energy supply and demand relationships. Under the backdrop of carbon neutrality, carbon trading costs have been gradually incorporated into dispatch models, focusing the economic objective not only on energy itself but also on establishing a balance between carbon emissions and economic benefits [14].

In grid-connected scenarios, rational wind-solar-energy storage scheduling can not only reduce dependence on grid electricity purchases but also sell electricity back to the grid during peak price periods, generating additional economic benefits. Under time-of-use electricity pricing mechanisms, energy storage systems can further enhance their economic operation by "charging during low-price periods and discharging during high-price periods." However, if short-term profits are pursued excessively, it may lead to accelerated aging of energy storage batteries and increased long-term replacement costs. Therefore, considering aging costs is crucial in economic optimization [4].

In recent years, some studies have also begun to include the value of ancillary services in economic assessments, such as the role of energy storage in providing frequency regulation, backup support, and peak shaving. These services not only improve the stability of the power grid but also boost the ROI of energy storage. Thus, the economic objective design is moving towards maximizing overall benefits, which involves a growth correlation of interests among various time scales and market players, to ensure that as many benefits as possible are maximized.

3.1.2 Reliability objectives

Reliability objectives have a direct impact on the power system, enabling it to safely and continuously operate in a stable manner. The usual measures of reliability are reduction of load shedding, maximum absorption rate of renewable energy, and system voltage and frequency stability limitations [15]. Extreme climates, failure, or tight power supply and demand conditions (characterized by large power supply and demand fluctuations) should be considered in dispatch strategies, with a focus on ensuring power supply to critical loads to prevent large-scale grid failures due to environmental instability.

The storage systems of energy are useful in improving reliability. The fact that they are capable of charging and discharging at any time means that they can effectively even out the irregularities of wind and solar power, making the system less prone to voltage and frequency variations that result from system imbalance [2]. It has been demonstrated that the four-quadrant capabilities of distributed battery energy storage systems make them particularly useful in optimizing node voltage. Optimization enables reducing the voltage difference to a minimum of 14.06 to 4.54 after optimization [6].

The reliability of the dispatch strategy level also differs at different operating modes. Wind-solar energy storage systems are considered a key resource in enhancing grid resilience. Their optimized dispatch not only minimizes the frequency and duration of power outages but also enhances the system's responsiveness in recovering from disturbances. Therefore, the design of reliability objectives must comprehensively consider safety, stability, and continuity to ensure robust operation of the system under complex conditions. In dispatch models with carbon trading mechanisms, carbon emission costs serve as a supplementary term to economic objectives. Dispatch optimization forms a dynamic game relationship between the economy and the environment [14].

3.1.3 Environmental objectives

With the advancement of global energy transition, environmental objectives are increasingly emphasized in wind-solar-energy storage dispatch models.

In microgrids and multi-energy systems, environmental objectives often form a dual constraint with economic objectives. The use of certain intelligent algorithms can achieve a dynamic balance between economic and environmental considerations. At the same time, some studies have also introduced a penalty mechanism for curtailment levels to indirectly reduce curtailment rates and further optimize environmental indicators. Therefore, environmental objectives not only reflect the direct environmental impact of system operation but are also closely related to the economy and reliability. Their design requires comprehensive optimization across multiple dimensions.

3.2. Constraint Analysis

In the optimization scheduling of wind-solar-energy storage systems, the setting of constraints is not only a prerequisite for the feasibility of the mathematical model but also an important part of ensuring the safe, stable, and efficient operation of the system. Common constraints mainly include power balance constraints, equipment operation constraints, energy storage constraints, and power grid safety constraints.

Power balance constraints are the foundation of dispatch models, requiring that the system must maintain a "supply and demand balance" at any given moment, meaning that the total power generation must be consistent with the total load [16]. When wind and solar power fluctuations are too large, relying solely on grid regulation can have an adverse impact on system stability. Therefore, energy storage plays a crucial role in balancing supply and demand, achieving peak shaving and valley filling, and smoothing power through dispatching.

Wind turbines, photovoltaic modules, and conventional units are all subject to capacity and operating curve limitations in actual operation. The output of wind power and photovoltaic power is usually determined by meteorological conditions and cannot be freely adjusted; conventional units, on the other hand, are affected by minimum operating power, ramp rate, and start-up and shutdown constraints [17]. These constraints ensure that the dispatch results are not only numerically feasible but also practically implementable in engineering.

The operating state of energy storage systems is constrained by factors such as charging and discharging power, state of charge, energy capacity, and efficiency, among others. Overcharging and over-discharging can shorten battery life, while maintaining a state of charge (SOC) that is too low or too high can affect the safe operation of energy storage. Therefore, upper and lower limits, as well as cycle life constraints, are usually set in dispatching [18].In addition, some studies have introduced energy storage degradation models to internalize battery aging costs into dispatch optimization, thereby enhancing the long-term sustainability of the model.

In grid-connected operation scenarios, the voltage stability, power flow distribution, and line transmission capacity of the power grid all impose restrictions on the dispatch plan [19]. If safety constraints are ignored, it may lead to overloading of certain lines or node voltage violations, thereby endangering system safety. Therefore, power flow equation constraints and voltage stability constraints are often introduced in optimization models to ensure that dispatch results comply with the standards of power grid operation.

Carbon trading structures, time-of-use electric charges, and ancillary service markets are all integral to achieving carbon neutrality and power market reform, where they exert an appropriate level of influence on dispatch decisions. These external conditions are not direct constraints, but they impose indirect constraints on the optimization model through price and incentives, influencing the ultimate dispatch outcome.

Overall, the constraints to wind-solar energy optimization scheduling are constituted by physical constraints and soft constraints at the market and policy levels. It is only through multidimensional constraints that the optimization model can ensure theoretical feasibility, as well as adhere to the engineering requirements for implementing this model.

4. Future Prospects for Wind-Solar-Energy Storage Optimization Scheduling

4.1. Technological Development Trends

The way optimization scheduling technologies for wind-solar-energy storage are developing is becoming smarter, more accurate, and flexible. The role of artificial intelligence technologies, particularly deep reinforcement learning, in optimizing the battery regime for wind-solar energy storage will become increasingly significant. Their versatility in adopting complex decision-making frameworks and acquiring the best strategies makes them the most effective instruments in managing highly uncertain and dynamic systems [3]. The use of hybrid energy storage systems will serve as a significant direction for future development, allowing for more efficient energy management. By implementing digital twin technology, wind-solar-energy storage systems will be controlled and regulated with greater precision, which will become a reasonable underlying practice.

4.2. Policy and Market Mechanism Improvement

It is essential to promote the development of wind-solar energy storage optimization scheduling through policy support and the enhancement of market mechanisms. More flexible and diversified electricity prices will play a leading role in the future, based on price signals that trigger the operation of energy storage systems and manageable loads in grid dispatching. The perfection of carbon trading systems and the slow rise in carbon prices will facilitate the sensible utilization of renewable and fossil energy. Emerging market forms, including distributed trading and peer-to-peer trading, microgrids, and distributed energy resources, will provide more direct market entry modes, decreasing transaction expenses and information asymmetry [7]. Moreover, the emergence of the energy Internet and the service of integrated energy will help clean up the value of various energy types and increase the overall system efficiency.

5. Conclusion

Energy storage, as an essential part of the smart grid, can be deployed to successfully counter the intermittency and uncertainty of renewable power through coordination and optimization scheduling, which can then improve the system's efficiency on an economic, control, and environmental sustainability level. Regarding dispatch strategies, day-ahead optimization scheduling, assisted by the forecasting mechanism, real-time rolling optimization scheduling, and a multi-time-scale coordinated mechanism for wind and solar power generation across all time scales can address fluctuations and prediction errors. With the unpredictability of wind and solar energy production, efficient methodologies exist for optimizing the process through robust optimization and scenario analysis.

Regarding optimization models, conventional optimization models, intelligent optimization models, and deep reinforcement learning models can all be used to achieve different kinds of dispatch problems. As demonstrated in practice, the optimization scheduling of wind-solar-energy storage has yielded greater outcomes in various cases, including microgrids, large-scale wind-solar-energy storage bases, and a combination of user-side energy storage and demand response. The scheduling of wind-solar energy storage will gain greater significance in the future, driven by enhanced technology and policy enhancements that promote energy transformation and the development of a clean, low-carbon energy system. To achieve this purpose, there is a need to conduct additional studies that reinforce the wind-solar-energy storage forecasting technology, develop multi-time-scale coordinated optimization techniques, investigate new market mechanisms, and integrate interdisciplinary approaches to promote prioritized innovation and improvement of wind-solar-energy storage optimization scheduling technologies.

References

[1] Fotopoulou Maria, Rakopoulos Dimitrios, Blanas Orestis. Day Ahead Optimal Dispatch Schedule in a Smart Grid Containing Distributed Energy Resources and Electric Vehicles. Sensors, 2021, 21(21): 7295.

[2] Chen Xiaojiao, Huang Liansheng, Zhang Xiuqing, et al. Robust Optimal Dispatching of Wind Fire Energy Storage System Based on Equilibrium Optimization Algorithm. Frontiers in Energy Research, 2021, 9: 754908.

[3] Li Yuanzheng, Yu Chaofan, Shahidehpour Mohammad, et al. Deep Reinforcement Learning for Smart Grid Operations: Algorithms, Applications, and Prospects. Proceedings of the IEEE, 2023, 111(9): 1055-1096.

[4] Li Yinxiao, Gu Yuxuan, He Guannan, et al. Optimal Dispatch of Battery Energy Storage in Distribution Network Considering Electrothermal-Aging Coupling. IEEE Transactions on Smart Grid, 2023, 14(5): 3744-3758.

[5] Yuan Jiaxin, Cheng Ke, Qu Kai. Optimal dispatching of high-speed railway power system based on hybrid energy storage system. Energy Reports, 2022, 8: 433-442.

[6] Li Xiangjun, Ma Rui, Wei Gan, et al. Optimal Dispatch for Battery Energy Storage Station in Distribution Network Considering Voltage Distribution Improvement and Peak Load Shifting. Journal of Modern Power Systems and Clean Energy, 2022, 10(1): 131-139.

[7] Cao Siming, Zhang Hanlin, Cao Kai, et al. Day-Ahead Economic Optimal Dispatch of Microgrid Cluster Considering Shared Energy Storage System and P2P Transaction. Frontiers in Energy Research, 2021, 9: 645017.

[8] Wang Guoying, Wang Chengfu, Feng Tianyuan, et al. Day-Ahead and Intraday Joint Optimal Dispatch in Active Distribution Network Considering Centralized and Distributed Energy Storage Coordination. IEEE Transactions on Industry Applications, 2024, 60(3): 4832-4842.

[9] Zhao Haizhou, Yang Junguang, Li Tieliang, et al. Coordinated Optimal Dispatching Method for Distributed Energy Storage and Distribution Network Under Multi-time Scale. 2023 International Conference on Electrical, Energy and Manufacturing Technologies (ICEEMT), 2023: 403-406.

[10] Garrido Victor, Gil-González Walter, Montoya Oscar, et al. Optimal Dispatch of DERs and Battery-Based ESS in Distribution Grids While Considering Reactive Power Capabilities and Uncertainties: A Second-Order Cone Programming Formulation. IEEE Access, 2024, 12: 48497-48510.

[11] Lu Di, Peng Yonggang, Sun Jing. Dual-Stage Optimization Scheduling Model for a Grid-Connected Renewable Energy System with Hybrid Energy Storage. Energies, 2024, 17(3): 737.

[12] Mao Yunshou, Cai Zhihong, Jiao Xianan, et al. Multi-timescale optimization scheduling of integrated energy systems oriented towards generalized energy storage services. Scientific Reports, 2025, 15(1).

[13] Xu Yilin, Hu Zeping. Source-Grid-Load Cross-Area Coordinated Optimization Model Based on IGDT and Wind-Photovoltaic-Photothermal System. Sustainability, 2024, 16(5): 2056.

[14] Zhou Wei, Sun Yonghui, Zong Xuanjun, et al. Low-carbon economic dispatch of integrated energy system considering carbon trading mechanism and LAES-ORC-CHP system. Frontiers in Energy Research, 2023, 11: 1134221.

[15] Ma Shiqian, Xiang Tianchun, Hou Kai, et al. Spatial–temporal optimal dispatch of mobile energy storage for emergency power supply. Energy Reports, 2021, 8: 322-329.

[16] Leon H., Yoon Sung-Guk. Combined Optimal Planning and Operation of a Fast EV-Charging Station Integrated with Solar PV and ESS. Energies, 2021, 14(11): 3152.

[17] Vasylyev Andriy, Vannoni Alberto, Sorce Alessandro. Best Practices for Electricity Generators and Energy Storage Optimal Dispatch Problems. Journal of Engineering for Gas Turbines and Power, 2023, 146(3).

[18] Yi Ji-Hyun, Cherkaoui Rachid, Paolone Mario, et al. Expansion planning of active distribution networks achieving their dispatchability via energy storage systems. Applied Energy, 2022, 326: 119942.

[19] Thirunavukkarasu Gokul, Seyedmahmoudian Mehdi, Jamei Elmira, et al. Role of optimization techniques in microgrid energy management systems—A review. Energy Strategy Reviews, 2022, 43: 100899.