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Intelligent Dispatch and Configuration Strategies for Wind–Solar–Storage Smart Grids

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Abstract. The coordination of wind, PV and PV systems in electricity networks has become one of the most important drivers for the green growth of electricity systems as the energy transformation and carbon neutral initiatives are being taken forward. In this article, we discuss the Intelligent Wind Solar Storage Network with a detailed description of its basic structure, operating principles, and present development situation. Based on the analysis of documents and examples, we have found that Model Predictive Control (MPC) and DRL (DRL) have proved to be economically efficient and flexible in distributing and storing power. Based on the examples from Qinghai, German and Shanghai, we find that the integration of wind and solar energy can increase the efficiency of RES and keep the electricity network stable. The research shows that the integration of artificial intelligence and the new generation of communication technology will become a key direction for the intelligent and coordinated development of wind-solar-storage systems in the future.

Keywords: Wind-Solar-Storage System, Smart Grid, Optimal Dispatching, Energy Storage Configuration, Artificial Intelligence

1. Introduction

Against the backdrop of the continuous advancement of global energy transition and carbon neutrality goals, the in-depth integration of wind power generation, photovoltaic power generation, and energy storage technology has become an important path to promote the optimization of energy structure and the green and low-carbon transformation of power systems [1]. Through the multi-energy complementation mechanism, the wind-solar-storage system can significantly improve the integration of renewable energy and the flexibility of power grid operation, which is of great importance for building a clean and efficient energy system [2]. However, the volatility and intermittency of wind and solar resources lead to unstable power output, and the energy storage system also has certain constraints in terms of cost and efficiency. The coordinated optimization and intelligent dispatch of the wind – solar – storage system have increasingly become core challenges as smart grids are being developed.

The current studies are mainly concerned with the problem of system modeling, power management, power storage configuration optimization, and scheduling strategy [3].

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Advances have been achieved, particularly in the application of smart algorithms like MPC and DRL. But there are many problems in the research, for example, the lack of multiobjective coordination, the lack of consideration for the degradation of the energy storage and the simplified operating restrictions, which makes it necessary to increase the overall performance and usability of the system in a complicated operational environment [4]. In this artiacle, we examine the Wind Solar Storage Intelligent Grid System, and make use of documents and examples to research its structure, operating mechanism, and optimizing tactics.

In this paper, a kind of smart scheduling frame is presented, which is MPC, DRL, and so on. Based on the comparison between Qinghai, German and Shanghai examples, this paper also proves that the integration of wind and solar energy can increase the efficiency of energy use and the stability of the network. The purpose of this study is to supply theory and methodology for high efficiency scheduling and smart exploitation of wind energy storage system.

2. Overview of wind-solar-storage smart grid system

2.1. System composition and principles

The wind-solar-storage smart grid system is composed of wind power generation, photovoltaic power generation, energy storage units, power grids, energy management systems, and communication networks. Wind and photovoltaic generation units are the core renewable energy sources in this system, generating electrical energy. Energy storage units maintain the balance of the power generation system by storing excess energy and releasing it when needs arise. Power grids are responsible for the transmission and distribution of electrical energy and maintaining the stability of the entire system. An energy management system acts as the central controller, conducting monitoring and dispatching for all subsystems. A communication network is built for information transmission and remote control, forming the development infrastructure for the operation of the entire system.

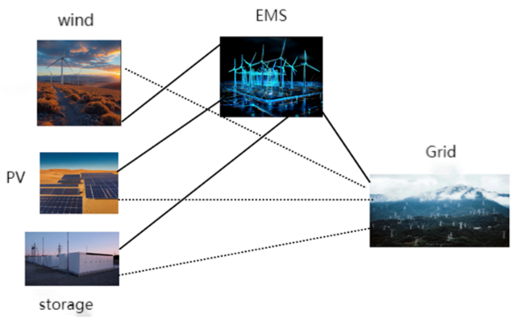

Figure 1. System architecture of the wind–solar–storage smart grid

As shown in Figure 1, the system architecture is composed of wind, photovoltaic (PV), and energy storage (ES) units on the left; the communication and energy management system in the center; and the power grid on the right. Solid lines denote data interaction, while dashed lines denote energy flow. Through the coordinated operation of these components, the system facilitates wind-solar complementation and intelligent energy management. Such coordination increases the use of renewables and makes the electricity network operational stable.

The running of this system is based on the physical model of every element. Wind power is mainly dependent on the wind velocity, the swept surface of the rotor, and the air density. Its classic

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mathematical expression can be written as follows: $P_w = \frac{1}{2}\rho A C_p v^3$, where ρ is the air density (kg/m³), A is the swept area of the wind turbine rotor (m²), C_p is the power coefficient, and v is the wind speed (m/s).

The results show that there is a high degree of variability and regional dependence of wind power, thus requiring strict requirements for scheduling and storing of energy.

The PV module's output power is determined by its surface area, optical strength, and photoelectricity conversion efficiency. Its mathematical model can be expressed as:

$P_{pv} = \eta A_{pv} G_t$; in the formula, η is the output power of photovoltaic energy, A_{pv} is the area of the PV panel (m²), and G_t is the solar irradiance (W/m²).

This model demonstrates the linear relationship between photovoltaic output power and irradiance. Simply put, the output power of the PV units varies directly with the light conditions, so it is necessary to integrate real-time meteorological data for power prediction and optimization control during system dispatching.

As a key regulation component of the wind-solar-storage system, the operating state of the energy storage units can be described by the energy balance equation.

The charging and discharging process of the energy storage system can be expressed as: $E_{t+1} = E_t + \eta_c P_c \Delta t - \frac{P_d}{\eta_d}\Delta t$; in the formula, E_t and E_{t+1} respectively represent the energy state of the energy storage unit at time t and $t+1$ (kWh), η_c and η_d are the charging efficiency and discharging efficiency respectively, P_c and P_d are the charging power and discharging power respectively (kW), and Δt is the time step (h). This equation reveals the dynamic change characteristics of the energy storage unit in the process of energy input and output, and provides a mathematical basis for system energy management and dispatching optimization.

2.2. Development status

Countries such as Germany and Denmark have promoted the high-proportion integration of renewable energy into power grids by constructing wind farms and photovoltaic power plants. For instance, Denmark has developed wind energy into one of its main power sources, and achieved high-penetration operation of wind power through cross-border power grid interconnection, flexible dispatching, and advanced prediction systems [5].

Qinghai Province is a leading country in the field of clean energy in China. Qinghai is known as "Clean Energy Demonstration Province" for its ability to develop wind power, solar power, and power generation. In 2021, the province implemented 20 market-oriented grid-connection projects, many of which utilized hybrid photovoltaic-wind-storage systems [6]. Not only was this a significant advance in the integration of renewables, it also provided a model for other provinces to follow. The Qinghai method has demonstrated that multi - energy coupling is feasible in technology and economy, and it is a useful tool to develop RES in all parts of China. Although they have a wealth of engineering experience, there are still some technical limitations and difficulties in applying them in the fields of scheduling arithmetic, lifetime of power storage and cost, safety of communication networks, and secure system stability.

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3. Wind-solar-storage smart grid system literature review

3.1. Technology application literature

The Model Predictive Control (MPC) and Deep Reinforcement Learning (DRL) have been extensively researched in the area of wind and solar energy storage. An innovative MPC-based frequency-regulating model for wind energy storage is described in the literature [7], for instance . Through the integration of Gray Theory in the Wind Velocity Forecast, the precision of the Model is improved significantly. This shows that prediction modeling combined with adaptive control is a promising approach to secure and responsive energy storage. Similarly, a multi-time-scale dispatch framework based on the Soft Actor-Critic (SAC) algorithm was established [8]. This framework utilizes the complementary features of batteries and supercapacitors in controlling long-term and short-term power fluctuations, respectively, thus promoting the economic and operational stability of the wind-solar-storage system, which highlights the advantages of reinforcement learning in coordinating multiple energy sources.

Besides these two methods, researchers have also achieved fruitful results in recent years in fields such as fuzzy logic control, heuristic algorithms (e.g., genetic algorithms, particle swarm optimization), and distributed optimization methods. Various optimization methods are applied in wind-solar-storage systems in many ways. First, for the fuzzy logic method, it does not need to establish an accurate mathematical model, so it can control the system stably even under multiple disturbances and uncertainties. Second, heuristic algorithms have a strong ability to optimize the global situation; therefore, they can also be adopted for the configuration and dispatching of energy storage capacity.

Finally, distributed optimization methods achieve coordinated optimization across multiple regions and energy units through parallel computation and information sharing. Comprehensively, existing studies on control strategies can be roughly divided into three categories: first, model-based optimization control (e.g., MPC), which emphasizes prediction and constraint solving; second, data-based intelligent learning (e.g., DRL), which focuses on strategy adaptation and optimal decision-making in complex environments; third, collaborative algorithms based on experience and distributed ideas (e.g., fuzzy control, heuristic algorithms). Different methods have their own advantages and shortcomings in terms of computational complexity, model dependence, and real-time performance, indicating that future research trends should further deepen in the integration of multiple methods and cross-scale coordinated optimization.

3.2. Analysis of literature on optimal dispatching

Optimal dispatching is central to maximizing the economic performance and operational reliability of wind–solar–storage systems. In terms of optimal dispatching, paper [9] studied the introduction of battery degradation cost constraints into dispatching strategies, and used deep reinforcement learning methods to achieve a balance between the long-term economy and operational stability of the system. Incorporating the lifespan decay factor into the reward function allows this study's dispatching strategy to consider not only the immediate benefits but also the life-cycle management of the energy storage system. In follow-up research, paper [10] proposed an end-to-end optimization framework using the Double Dueling Deep Q-Network (DQN). By combining market revenue with carbon emissions, peak load shaving, and battery degradation index into a single objective function, it is possible to optimize the economic and environmental benefits simultaneously. Systematic integration has shown strong learning decision-making capability under multi-objective complex

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conditions. It has effectively adjusted to dynamic price fluctuations in electricity markets and increased renewable energy penetration. Additionally, paper [11] achieved globally optimized energy storage capacity and dispatching strategy for a wind-solar-storage system through a Genetic Algorithm (GA), reducing the operating cost by 12%. The above methods, however, are still inefficient in collaborating decision-making across different time scales and have limited effects on external uncertainty. This indicates the potential advantage of hybrid or adaptive optimization methods in dealing with the randomness and uncertainty of renewable energy.

A comprehensive review of the above studies shows that reinforcement learning-based methods have obvious advantages in handling high-dimensional dynamic optimization problems, while traditional optimization methods based on heuristic algorithms still retain value in global optimization and engineering feasibility. However, the bulk of current studies still focus on theoretical modeling and algorithm verification. The integrated consideration of battery aging model accuracy, dispatching real-time performance, and multi-energy collaboration constraints is not enough. Then, deep research will be needed to explore scheduling frameworks that combine several algorithms to realize cross scale optimization.

3.3. Induction of literature on development challenges

Although many advances have been made in the field of modeling and control policies, the current work is facing a number of technological and application challenges . Past research has shown that during long periods of use, the cells tend to experience a significant decline in volume and a progressive decline in energy efficiency, and their deterioration depends strongly on the temperature, the depth of the discharge, and the number of cycles [12]. The reliability of lifespan modeling significantly impacts the economic assessments and dispatch optimization of energy storage systems. Therefore, the formulation of a reliable battery fading model is of paramount importance to improve the precision of the system and to support long term operation.

In addition, low power wide area communication techniques such as NB-IoT have been reported to be prone to interference and data loss in complicated electromagnetic fields, resulting in reduced communication reliability [13]. These constraints limit the application of wind solar energy storage in real time surveillance and smart distribution. The poor reliability of the communication level threatens the accuracy of Energy Management System (EMS), but it also exposes weaknesses in the current intelligent grid's information safety and network resilience.

In summary, energy storage unit degradation modeling and communication network stability are pressing bottlenecks hindering research on wind-solar-storage microgrids. Future research will focus on the study of electrochemistry mechanism, status prediction, and network failure tolerance for complex situations.

3.4. Comprehensive literature review

Most of the papers focus on the single optimal objective, for example, the minimization of the cost or the maximum of the energy efficiency, and the lack of focus on multiobjective cooperation, interdisciplinarity, and project execution.

The table 1 compares the main technologies underlying the Intelligent Grid Based on Wind and Solar Energy in terms of their merits, constraints and functions in the Integrated Framework.

The integration of AI, Large Data, 5G or 6 G in the future will push forward the integration and deployment of wind and solar energy.

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Table 1. Comparison of key technologies in wind–solar–storage smart grid systems

Technology	Advantages	Shortcomings	Role in Wind-Solar-Storage System
Wind Power Generation	Clean energy, great large-scale development potential	High volatility, affected by climate	Provides large-scale clean electricity
Photovoltaic Power Generation	Modular design, short construction period	High dependence on day-night cycles and weather	Distributed integration, peak shaving and valley filling
Battery Energy Storage	Fast response speed, bidirectional regulation	Relatively high cost, limited service life	Smoothing power output, peak shaving and valley filling
Pumped Storage	Large capacity, long service life	Long construction period, geographical restrictions	Providing long-term energy balance

4. Conclusion

4.1. Analysis of practical applications

Wind and solar energy storage is an excellent example of being versatile and adaptable in a wide range of practical applications. The establishment of an autonomous micro-grid in a remote area enables power independence and localization to be managed in a more efficient manner to stabilize and increase the reliability of the local power supply. In the context of an industrial park, the energy-storing units help to adjust the peak load, fill the valley, and regulate the load, thus lowering the cost of power, as well as encouraging the use of green energy.

In a city's electricity network, wind and solar energy can be used to strengthen the regulatory capability of the network by supporting large scale distribution of renewables. The advantages of this kind of system are adequately demonstrated by actual engineering applications. In Hainan Prefecture, Qinghai Province, multiple energy complementary demonstration projects have been successfully implemented by combining wind power, solar power and power storage [14]. Likewise, Fraunhofer ISE in Germany introduced a wind and solar energy storage system in an industrial zone, which is currently being utilized as a cost efficient means of balancing the load and thus reducing power costs by about 15%. In addition, Zhangjiang Smart Park of Shanghai is equipped with dynamic coordination of PV and PV systems, which is built on AI Routing Platform to improve the efficiency of energy use and decrease CO2 emissions from urban areas.

4.2. Optimization strategies

Research has been done on the problem of the optimal design of the system from a variety of angles, including the control algorithm, the energy-storing configuration, and the multiple-energy collaborative design.

In order to improve the ability of power management and scheduling, AI techniques such as Reinforcement Learning, Deep Neural Networks, etc [15]. For this reason, we have developed a Soft Actor-Critic (SAC) algorithm for multiple time scales to optimize and allocate power between cells and super capacitors, thereby greatly improving operation stability and economic efficiency.

Finding a good balance between ROI and ROI by capability matching and full life cycle cost-benefit analysis is the main method of selection in EPM. Using the LCOE model, an economic assessment of a battery's investment can be used to provide a data-based guide to the planning and operation of the system.

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Furthermore, in the area of multi - energy complementarity, wind solar and solar power are combined with other technologies like EV and H2 to build a more flexible comprehensive energy system [16]. Research shows that a low carbon complementary "Wind Solar Storage + Hydrogen Power" alternate mode can be used, which is different from the initial path of large-scale RES projects, which is more flexible, sustainable and low carbon.

Generally speaking, adopting the Dimension Analysis Optimization Method will enable the Wind and Solar Storage Systems to maximize their operating efficiency and economy, thereby establishing the technological basis for an effective and coordinated operation in the future.

5. Conclusion

The Intelligent Wind and Solar Electricity Network as a key framework to move to a low-carbon economy in the future, is a key element in building a clean, effective and safe energy system. Digital management is used to make sustainable wind and solar energy available in order to transform them into clean energy, thus improving the operation flexibility and stability of the electricity network, while achieving a system optimal benchmark. The structure, control policy and optimal route of wind and solar energy are summarized in this paper. It is shown that the above-mentioned features can improve the efficiency, agility, and intellectual performance of wind and solar energy. At this point, however, there are many problems with the use of wind solar energy storage systems, mainly because of the limitations in the modeling of their life cycle, the poor reliability of the communication network, and the absence of cross-region collaboration.

As part of the "Carbon Cap, Carbon Neutral" policy, the next phase will be to integrate smart mining and data-based technologies into wind and solar energy storage. Taking advantage of AI, Large Data Analysis and High Speed Next Generation Communication Techniques will offer a high level of flexibility and optimal deployment. Furthermore, the development of new and modern technologies like hydrogen-powered, EVs, VEVs and EVs, as well as energy-storing systems, will extend the possibilities of actual use of wind and solar storage systems in order to achieve a cross-region collaboration that would be complementary to the various energy frameworks in order to ultimately build an integrated global energy system. Generally speaking, the continued deployment and deployment of intelligent wind and solar power generation is important not only to meet domestic carbon objectives, but also has great potential to optimize the conversion of future energy assets into a more effective and cleaner way.

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