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Coordinated Scheduling Strategy for Demand Response in Smart Grids Under High Proportion of New Energy Integration

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Abstract. With a large number of high proportions of new energy sources being integrated into the power system, the uncertainty of supply and demand in system operation has significantly increased. The traditional scheduling model - the source-tracing load model has been unable to meet the new demands. This paper mainly discusses the demand-side response of the smart grid in the context of a high proportion of new energy. It focuses on a minimization scheduling model, which involves the coordinated operation of sources and loads to maximize the economic benefits of resource allocation and the absorption capacity of new energy. Through theoretical research, performance comparison, and multi-scenario simulation methods, a resource collaborative optimization framework based on group intelligence was established. The study shows that this method can reduce the overall investment of the energy system by approximately 12% and lower the operating costs by 5% to 12%. It is applicable at the park level and in multi-purpose scenarios, effectively improving the utilization rate of new energy and enhancing the stability of the power grid. It was found that demand-side collaborative scheduling is the most critical path to achieve the transformation of the power system from the source-following mode to the source-load interaction mode. By adopting innovative system architectures and technology integration, this method can systematically address the current challenges and promote the sustainable development of the new power system.

Keywords: High proportion of new energy, Smart grid, Demand response, Coordinated scheduling

1. Introduction

The power system is gradually shifting from a structure dominated by fossil energy to a new one led by clean energy, driving the transformation of the energy system towards a green and low-carbon direction. The large-scale integration of high proportions of new energy sources, such as wind power and solar energy, has presented new challenges to the operational pattern of traditional power grids. Bai et al.'s research on the impact of large-scale integration of new energy sources on smart grids indicates that most of the new energy generation has volatility and may cause a grid to lose stability

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within a short period of time [1]. Therefore, in order to achieve stable power output in the smart grid and avoid unnecessary energy waste, it is necessary to develop a reliable coordinated scheduling plan for the new energy era.

With the continuous growth of the share of renewable energy sources, the resulting supply-demand uncertainties are difficult to address within the traditional dispatch mode of "power generation following load" (that is, the power generation side dynamically adjusts its output based on the real-time fluctuations of the load side to ensure the balance of power supply and demand). At present, most of the research on the source-load side focuses on individual source-load side optimization or local coordination, and there has not yet been a systematic synergy effect. In particular, the massive distributed resources and centralized new energy power stations lack effective coordination in the context of the smart grid, resulting in low scheduling efficiency, difficulty in forming the aggregation effect, and even the possibility of creating new peak-valley load problems. This is also a current challenge faced by the power industry in China, and it is also a problem currently encountered by the power industry in China.

Therefore, this paper focuses on the demand-side response of the smart grid under the background of a high proportion of new energy integration, and aims to study the coordinated dispatch strategy of power sources and loads. The aim is to achieve the optimal allocation of system resources, promote the efficient utilization of new energy, and ensure the safe and stable operation of the power grid. By establishing an effective collaborative mechanism, the capacity for absorbing new energy can be enhanced, and the waste of wind and solar resources can be reduced.

2. Theoretical foundation analysis

2.1. System architecture - intelligent grid structure with high proportion of new energy integration

The currently widely recognized architecture of the smart grid system is shown in Figure 1. This system can be divided into four layers, namely the physical layer, the information layer, and the application layer. Moreover, a unified communication network and security protection system runs through all of them. However, this hierarchical and collaborative architecture system is now facing entirely new challenges brought about by the large-scale integration of new energy sources. The integration of new energy sources has brought about fundamental changes compared to traditional power grids. The instability of the natural environment leads to uncontrollable output power of the smart grid, which imposes great pressure on the power balance and stable operation of the smart grid. For instance, wind power generation has characteristics such as randomness and intermittency, which have certain impacts on the stability of the power grid [2]. In the face of challenges, the intelligent power grid, which consists of five components including electricity generation, electrical transformation, power conveyance, electricity distribution, and electricity utilization, requires the use of real-time monitoring and related technical means such as interconnection and communication, and aims to achieve the automation, intelligence, safety and reliability of the power system operation [3]. Figure 1 shows the core architecture and data flow of smart grid technology research and development.

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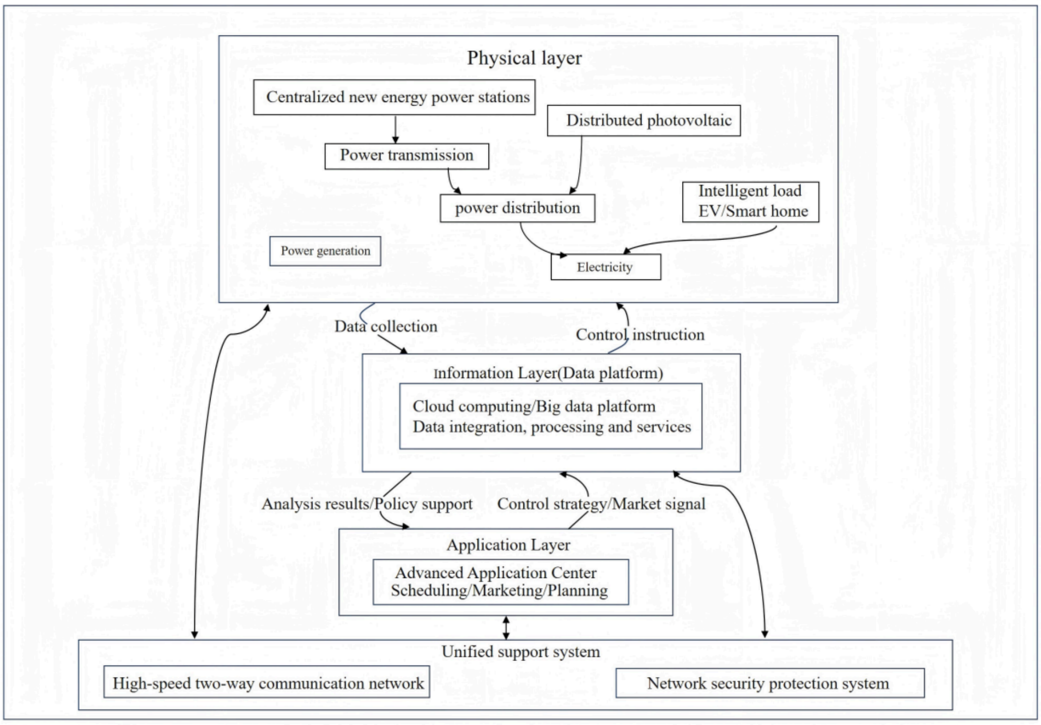

Figure 1. Architecture diagram of smart grid (original)

2.2. Demand-side response collaborative scheduling strategy

The demand-side collaborative scheduling strategy for smart grids integrates modern information communication, precise metering, and intelligent control methods to conduct cluster aggregation, real-time monitoring, and collaborative optimization control of the terminal load resources in the power system. It establishes a dynamic response mechanism with the characteristics of renewable energy generation and the grid operation conditions, achieving comprehensive improvement in system safety and stability, economic dispatch, and low-carbon environmental protection.

A swarm intelligence-based collaborative optimization scheduling architecture has been developed and marketed to achieve better efficiency in scheduling and better response ability of systems. In the event that the cloud-edge integrated smart scheduling system is implemented in the new energy power grid, the power system will have the opportunity to transition from being load-controlled to attain a source and load interaction state. It is based on the use of virtualization technology to interconnect underlying hardware resources, and using the distributed architecture, it considers computation, storage, and network devices to deliver an end-user with scalable computing power and dependable data services [4].

Associated with optimization of the scheduling architecture is the establishment of the demand-side response mechanism. The demand-side response in a price manner is optimal, maximizing the accuracy of the matching of power supply and demand across time and space, improving the efficiency of clean energy consumption, smartly controlling peak and off-peak loads, and lowering the cost of setting up reserve capacity, grid security, and system-economic profit. This mechanism will make the grid location more risk-resilient, will slow down the expansion of the power transmission and transformation facilities, and will support, on a market-based basis, the construction of power systems characterized by the prevalence of new energy.

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The combination of maximizing the scheduling architecture and the demand-side response mechanism has excellent application benefits in extreme cases. This mode shows its value of application in cases of extreme weather conditions or other emergencies rely on the flexible allocation of resources. The smart load control in the peak time saves the use of traditional peak-shaving capabilities like coal-fired power plants.

3. Performance comparison (compared with traditional scheduling methods)

3.1. Construction costs, operating costs, and investment returns — all these need to be taken into account

The reaction process on the demand side can ensure the efficiency of the economy and the running of the energy system. Xu remarked that the sum of investment in the energy system under the demand-side response mechanism was some 12 percent less than the sum under the scheme of the baseline [5]. Kiptoo et al. indicated that demand-side response in terms of peak shaving and valley filling allows operating costs to be lowered by around 5% -12% to the operating cost when the scheme was not utilized by schemes that used DR [6]. Concerning the element of returns on investment, the economic worth of the demand-side collaborative working of the new energy intelligent power grid has multi-dimensional features. It is the combination of these two dimensions that eventually turns into a path of upgrading the power system of safety, efficiency, and environmental friendliness, thus the exceptional value of investment that combines economic advantages and social ones. Table 1 below is a comparative analysis of the different performances by the two strategies as discussed below:

Table 1. Performance comparison and analysis relative to traditional scheduling strategies

Comparison dimension	Specific content	Data / Effect	Reason/ Mechanism
Construction cost [5]	Total investment in the energy system	Reduce by approximately 12%	Since the demand-side response mechanism was rolled out, the load on the transmission and distribution network has dropped noticeably, and energy storage devices are now getting much more refined scheduling and utilization.
Operating costs [6]	Overall operating cost	Decreased by approximately 5% to 12%	Through demand-side response for peak shaving and valley filling
Investment returns	Economic value characteristics		Multidimensional characteristics, including quantifiable immediate benefits and potential scalability advantages
	Operational efficiency		Reduce the expansion pressure during peak load periods of the power grid and the expenditure on emergency reserves, thereby creating price discount space for participating regulating users.
	The role of energy transition		Optimizing the grid's mechanism for absorbing intermittent renewable energy sources can alleviate the dilemma of renewable energy being discarded and enhance the stability of the power supply system.
	Final value manifestation		A power system upgrade path that checks all the boxes: safe, reliable, efficient, and environmentally friendly. What makes it stand out is its unique investment value, blending economic returns with social benefits seamlessly.

3.2. Energy efficiency improvement and environmental benefits

According to studies of smart grids, it has been noted that the demand-side response collaborative scheduling strategy, whereby distributed flexible loads are coordinated with the intermittent renewable energy sources like wind power and photovoltaic power, can ensure the dynamic nature of power system supply and demand. This system circumvents the shortcomings of the conventional

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oversight strategy that merely depends on the peak-load regulation of the power generation part. Rather, it brings a coordinated control of the supply and demand side, maximizing the load curve, helping to reduce grid congestion, minimizing transmission losses, and encouraging the timely and geographical alignment of the pattern of power consumption to the nature of new energy sources. The study by Bai et al. has proved that demand response can be considered to increase the flexibility of the uncontrolled loads that can be regulated, and convert them into new system resources that can balance the ad-hoc changes in new energy generation [7]. The proposed control strategy will enhance the percentage of wind power use by about 35 percent when the amount of electric power discharged by the power generation side remains steady, but by over twenty percent when the carbon emissions are minimized. This empirical information has confirmed the validity of the demand-side response corrective measure to address the issue of renewable energy consumption, and generate key technical support on the green and low-carbon transformation of the energy structure of China, and reach the coordinated optimization of the working efficiency of the energy system and environmental sustainability objectives [8].

4. Application scenarios/objects

Through verification of examples in different scenarios and analysis of relevant data, it has been shown that, against the backdrop of a high proportion of new energy integration in China's power system, the demand side response collaborative scheduling strategy of the smart grid has important application value.

The application of this strategy has achieved good results in a photovoltaic storage and charging integrated micro-grid park in Haining, Zhejiang. In addition, when applying virtual power plants in the electricity market environment, by applying virtual power plants to virtual power stations, it can achieve market synergy and clearance [9]. The specific results have been demonstrated in the zero-carbon demonstration park of Jinji Lake Business District in Suzhou Industrial Park. These application scenarios are all based on bidirectional interaction between source and load to achieve optimal allocation of system resources and put the power system on a clean and intelligent track of development (Table 2).

Table 2. Comparison of example effects and data analysis of different scenarios

Applications		Actual effect	Scenarios/objects
Suzhou Taihu Lake New Town Carbon Neutralization Demonstration Zone	Consumption of new energy at the point of use (CNEPU)	Through multifunctional collaborative scheduling, the comprehensive energy utilization rate of the region is boosted. The on-site consumption rate of distributed photovoltaic power generation in the region has increased, promoting the use of clean energy.	The CNEPU has reached 98%.
	Reduce cost and increase efficiency.	By optimizing resource procurement and operational strategies, the overall energy consumption cost within the region has been reduced. For example, during the peak period of electricity bills, The system will prioritize the use of energy storage and local photovoltaic power, reducing high-priced online shopping for electricity.	The cost reduction and efficiency improvement rate has reached 10-15%
A microgrid park integrating photovoltaic energy storage and charging in Haining, Zhejiang Province.	CNEPU	Consumption of new energy at the point of use: Increasing the proportion of self-use photovoltaic power generation within the park greatly reduces carbon emissions. Reduce cost and increase efficiency. Utilizing energy storage for peak valley price arbitrage to save electricity expenses for the park.	The CNEPU has reached 85%.
	Reduce cost and increase efficiency.		Reduce costs and increase efficiency by 500000 yuan, with a cost reduction and efficiency increase rate of 12%.

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Table 2. (continued)

Suzhou Industrial Park Jinji Lake Business District Zero Carbon Demonstration Park	rate of on-location utilization of renewable energy sources Reduce cost and increase efficiency.	CNEPU: The park focuses on a combination of commercial and office scenarios, building a "photovoltaic+energy storage+combined cooling, heating and power" system. The photovoltaic energy stored in office buildings during the low valley period at night is allocated to the peak commercial electricity consumption during the day. After the project is put into operation, new energy can be consumed on-site. Reduce cost and increase efficiency: The overall energy consumption cost of the park has significantly decreased, and the carbon dioxide emissions have decreased.	The CNEPU has reached 75%. Reduce costs and increase efficiency by 1 million yuan, resulting in an overall energy cost reduction of 18%.

5. Challenge and optimization analysis

Although the demand side response collaborative scheduling strategy has obvious advantages, However, there are still some shortcomings in practical promotion and application. Firstly, in terms of resource aggregation and regulation, distributed load resources have a large quantity and diverse types, and their response behavior exhibits strong uncertainty and spatio-temporal dispersion. It is not easy to achieve unified scheduling and control. Secondly, in terms of technical support, to truly achieve efficient "source load" interaction, Higher requirements need to be placed on the system's information infrastructure, establishing a high-speed, stable, and reliable communication network and strong data processing capabilities [10]. Thirdly, in terms of market mechanisms and policy environment, the demand side resources in the current electricity market do not yet have a clear and accurate market positioning, as well as a reasonable and effective compensation mechanism, Lack of long-term and stable policy guidance and economic incentives, The enormous cost of economic construction will undoubtedly become one of the challenges for the popularization of new energy smart grids [11]. Fourthly, on the user side, the response to electricity price signals or control instructions also has a significant time delay and randomness. It is difficult to ensure the stability and reliability of the overall scheduling effect. To address the above issues, improvements can be made in the following aspects:

Build a hierarchical partition control structure, Namely "cloud edge end", Realize self governance of load resources within a local area; Furthermore, starting from the entire system, it will carry out global optimization planning, Capable of fully coordinating work at the source, network, and various stages, To achieve a balance between supply and demand; Infuse load forecasting, behavior modeling, intelligent decision-making, and other related tasks throughout the entire process, Utilizing artificial intelligence and big data technology to make regulation more precise and rapid; Improve the electricity market mechanism, Develop market-oriented products suitable for high proportion new energy access such as real-time electricity prices and capacity markets; Intensify standardization efforts, Improve the communication protocol interface standard system for opening up to the outside world, Realize inter-connectivity and collaborative operation between multiple power sources/load nodes [12]

6. Conclusion

Through systematic research on the collaborative scheduling problem of demand side response in smart grids, based on the analysis of CNEPU and data results, the main conclusions drawn under high proportions of new energy access conditions are as follows:

Demand side response collaborative scheduling is a technical means to promote the transformation of the power system from "source following load" to "source load interaction",

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Further enhance the capacity to accept new energy, reduce system operating costs, Improve the safety, stability, and operational flexibility of the power grid; Establish a clean, low-carbon, safe, and efficient new power system. It needs to utilize advanced methods such as price guidance, cloud edge collaboration, and virtual power plants. Realize flexible aggregation and efficient regulation of distributed resources. There are certain difficulties, Mainly due to the need for improvement in resource aggregation, communication support, and market mechanisms, But breakthroughs can be achieved through various means such as reasonable architecture design, technological integration, and innovative market mechanisms; Actively drawing on the business models of advanced technology applications, Make corresponding pioneering and innovative attempts in the coordinated scheduling mechanism of demand side response for new energy supporting peak shaving, Faced with China's goal of peaking carbon emissions and achieving carbon neutrality, And the contradiction problem under the vigorous development of new energy installed capacity, it should accelerate the development of new digital technologies such as artificial intelligence, the Internet of Things, and blockchain.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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