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Analysis of the Characteristics and Applications of Wind-Solar-Storage Systems in the Smart Grid

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Abstract:

At present, with the rapid development of smart grid, scenery storage system, as the core carrier of multi-energy complementarity, has shown significant advantages in improving the energy absorption capacity of renewable energy, enhancing the flexibility and stability of power grid. However, the intermittent and uncertainty of renewable energy generation poses many challenges to the grid operation. This paper takes wind energy, photovoltaic and energy storage as the basic entry point, combines the actual situation, extends the overall architecture of the landscape storage smart grid and analyzes the architecture. Then, the key technologies of the wind light storage system under the background of the smart grid are systematically analyzed. For example, the characteristics and application progress of technologies such as renewable energy grid, energy storage, demand side response, virtual power plant and other technologies, although these technologies have been successful, some problems remain. At the end of this paper, the research bottlenecks, optimizable items and prospects for the future are also discussed.

Keywords: Wind and solar energy storage; smart grid; renewable energy sources; grid security.

1. Introduction

At present, human society is confronted with the dual severe challenges of energy and the environment. The extensive consumption of fossil fuels has led to severe environmental pollution and climate change problems, which have become the focus of global attention. Therefore, developing clean and renewable green energy has become an inevitable choice. Wind power generation and solar power generation, as the most representative green energy sources, have developed rapidly worldwide due to their characteristics such as low cost, cleanliness and renewability. However, the intermittency and uncertainty of wind and solar power generation also bring new challenges to the operation of the power grid. How to effectively integrate and consume wind and solar power generation by using smart grid technology and improve the flexibility and reliability of the power grid has become a key research direction in the current energy

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field [1]. However, there are still some deficiencies in the current research. For instance, the optimized scheduling strategies for large-scale wind-solar-storage systems and the intelligent energy management of multi-energy coupling still need further in-depth exploration.

As the direction of power grid development in the 21st century, the smart grid, through the deep integration of information technology, can achieve two-way interaction, self-diagnosis and self-repair of the power grid, providing technical support for the high proportion of clean energy access. Against this backdrop, the wind-solar-storage smart grid system emerged. This system integrates wind power generation, solar power generation, energy storage technology and advanced information and communication technology, achieving clean production, efficient storage and intelligent allocation of electricity, and providing key technologies for building a clean and low-carbon power system [2].

This article mainly focuses on conducting research reviews in aspects such as system architecture design, key technological innovation, and operation optimization. In terms of system architecture design, through distributed and modular design, how to improve the flexibility and reliability of the system; In terms of key technological innovation, it involves the grid connection of new energy, the optimization of energy storage technology, virtual power plants, etc., as well as the advantages and development bottlenecks of these technologies and their impact on the smart grid.

2. Wind and Solar Storage Smart Grid System Architecture

2.1 The Framework and Main Components of the System

As shown in Figure 1, from the perspective of the overall architecture, the wind-solar-storage smart grid system is composed of four core modules: the renewable energy power generation subsystem, diversified energy storage technologies (electrochemical,pumped,hydrogen energy,etc.), the digital monitoring system (PMU/SCADA combined with the Internet of Things and big data), and the intelligent security protection system. The system achieves clean energy supply through wind and solar power generation, balances the supply and demand of the power grid and optimizes power quality with multiple types of energy storage technologies, monitors the power grid status in real time with PMU and SCADA technologies, and realizes precise regulation and control relying on cloud computing.

Innovative technologies drive the intelligent upgrade of the system: Based on 5G communication and edge computing, multi-node collaborative control is achieved. Through AI algorithms, load forecasting on the user side and power scheduling on the power source side are completed, significantly enhancing the capacity to accommodate renewable energy. Deploy an adaptive security protection mechanism and combine it with the fault self-healing algorithm to achieve millisecond-level fault location and isolation. The system design emphasizes geographical adaptability and needs to be optimally configured in combination with regional resource endowments and load characteristics. For example, in areas rich in wind and solar resources, energy storage and peak shaving are emphasized, and in load centers, the demand-side response capability is strengthened, thereby achieving a dual improvement in energy efficiency and power supply reliability [3,4].

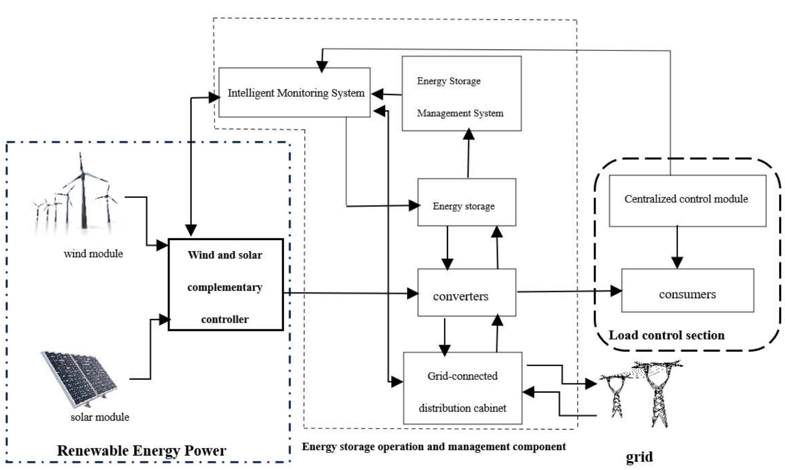

Fig.1 Framework diagram of the wind-solar-storage smart grid system

2.1.1 Wind power

Wind energy, as a renewable energy source, is widely used in countries such as Japan, the United States and Europe. This is because, compared with non-renewable fossil fuels like coal and natural gas, wind energy not only causes less pollution to the environment but also has a relatively lower cost. Wind power generation technology refers to the wind driving the rotation of wind turbine blades, which then drives the generator to generate electricity through the transmission system. Ultimately, mechanical energy is converted into electrical energy, and the principle is shown in Figure 2:

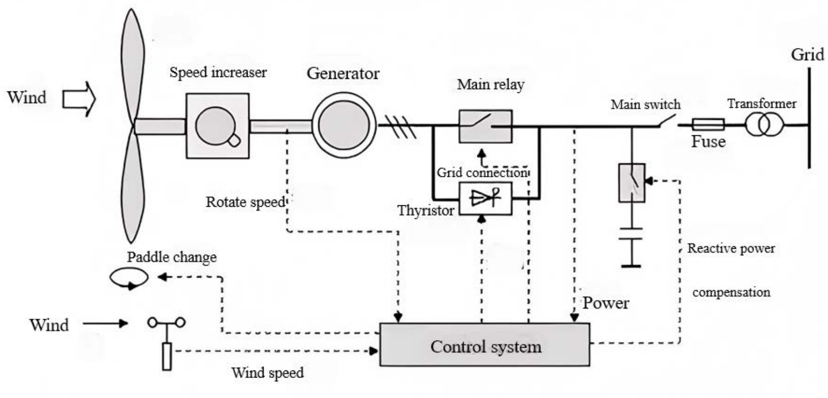

Fig.2 Schematic diagram of wind power generation

Due to the limitations of different wind turbine and blade technologies, China still mainly relies on horizont-axis wind turbines (HAWT) at present. When connected to the power grid system, the entire power system needs to make timely adjustments to the changes in wind force size. However, the output power of wind is difficult to accurately estimate due to the changes in wind speed. This poses a great challenge to the proper adjustment of the power grid [5].

2.1.2 Photovoltaic

After the new energy photovoltaic power stations are connected to the power grid, the proportion of renewable energy in the power grid has increased, promoting the optimization of the energy structure of the power grid. Distributed photovoltaic power can enhance the adaptability and flexibility of the power grid. It can relieve the pressure on the traditional power grid during peak electricity consumption periods and also store electricity when power demand is low. Centralized photovoltaic power transmission transmits the electricity from each photovoltaic power station to the distribution network center through high-voltage transmission lines and implements unified dispatching, which makes its transmission efficiency very high. The principle is shown in Figure 3.

However, due to the influence of the Earth's rotation and revolution, the power generation effect of photovoltaic power stations often shows periodic changes. Affected by weather and seasons, the instability of output power will directly affect the stability of the output power of the distribution network. This makes photovoltaic power stations highly dependent on the energy storage system of the distribution network, and it is necessary to ensure that the system responds correctly [6].

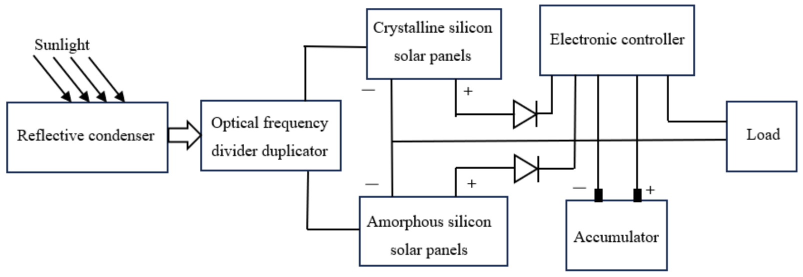

Fig.3 Photovoltaic power generation schematic diagram

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2.1.3 Energy storage

Energy storage technology refers to temporarily storing energy and releasing it when needed to provide electricity, thereby ensuring the stable operation of the power grid. However, due to the differences in working principles and energy storage media, energy storage systems can be roughly divided into two types: electrochemical energy storage technology and mechanical energy storage technology. The emerging compressed air energy storage technology, with its good energy-saving and environmental protection effects, it can not only effectively balance the load of the power grid, but also ensure the energy utilization rate. In China, the related industrialization process has significantly accelerated. As the compressed air energy storage system consists of components such as compressors, expenders, air storage chambers, heat storage tanks, and electric generators, it is a very complex energy flow system. In actual operation, the electrical energy generated by photovoltaic power generation or wind power generation is used to drive the compressor to move, forming compressed air, and the electrical energy will naturally be converted into the pressure energy formed when the compressed air is activated. During discharge, the expansion device is then used to restore the compressed air to kinetic energy. This project stores the compressed gas in specially designed pressurized containers and keeps them together in the underground gas storage chamber. It is also necessary to improve the overall energy utilization efficiency based on the interaction of different parts [7].

3. Key Technologies of Wind-Solar-Storage Smart Grid

3.1 Renewable Energy Grid Connection Technology

Renewable energy grid connection technology refers to the key technology of connecting intermittent and highly volatile renewable energy power generation systems such as wind energy, solar energy and hydropower to the power grid, and ensuring the stable operation of the power system through technical means. The core principle is to achieve synchronous matching of renewable energy generation and the power grid in terms of voltage, frequency, phase, etc. through power electronic devices, energy storage systems and intelligent control strategies, while optimizing power quality and system economy. It mainly includes: volatility management, power grid adaptability, intelligent regulation and control, etc [8].

Among them, in terms of grid-connected converters, the current mainstream technologies include current-controlled inverters and flexible DC transmission. Photovoltaic inverters prevent direct current from flowing into the grid through isolation converters, while wind power generation uses frequency converters to achieve frequency assimilation and reduce grid connection impacts. In terms of energy storage, pumped storage, battery energy storage and demand-side response have become the keys to enhancing system flexibility [9]. Research shows that configuring energy storage can reduce the rate of wind and solar power curtailment and balance intraday fluctuations in scenarios with a high proportion of new energy. Research indicates that diversified energy storage technologies are a key direction for future development. In terms of intelligent control and market transactions, microgrid technology based on droop control and oscillation identification technology based on width learning have enhanced the stability of local power grids. Meanwhile, market-based trading mechanisms, such as green power trading and ancillary service markets, promote consumption through economic incentives. In 2023, the proportion of market-based trading volume of new energy in China reached 30.1% [10]. Its operating framework is shown in Figure 4.

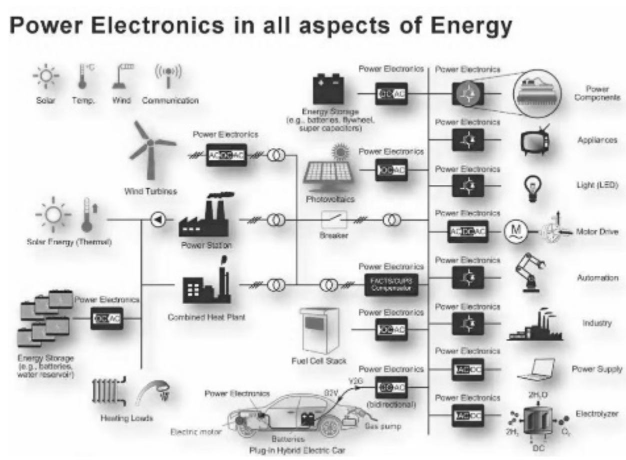

Fig. 4 Renewable Energy Grid Connection Schematic

Renewable grid integration reshapes smart grids' structure and operation, driving digitalization and flexibility. Volatility and low inertia intensify grid frequency/voltage regulation challenges, addressed by virtual synchronous machines (VSM) to emulate inertia, AI-enhanced wind/solar prediction accuracy, and flexible DC transmission paired with energy storage to suppress fluctuations [11]. Distributed energy systems rapidly evolve: high-altitude producer-consumer frameworks improve remote grid economics via hybrid storage and multi-energy synergy. Meanwhile, distributed PV's rapid adoption in central/eastern regions causes distribution network overloads, requiring optimized grid access capacity assessments.

3.2 Energy Storage Technology

Energy storage technology, as one of the pillar technologies of the smart grid, alleviates the intermittency and volatility of renewable energy through functions such as energy time-shift and frequency and peak shaving, ensuring the stable operation of the power grid. At present, energy storage technologies in smart grids can be classified into the following categories based on their principles:

Electrochemical energy storage Lithium-ion batteries are dominant (accounting for over 97%), while sodium-ion and flow batteries are gradually being promoted due to their cost and safety advantages. Mechanical energy storage. Pumped storage technology is mature but restricted by geography. Compressed air energy storage relies on salt cavern resources to achieve large-scale demonstration. Electromagnetic energy storage Supercapacitors and superconducting magnetic energy storage (SMES) support the instantaneous regulation of power grids with millisecond-level response capabilities. Hydrogen energy storage. As an ultra-long-duration energy storage technology, hydrogen production through electrolysis solves the problem of temporal and spatial mismatch of wind and solar resources. The technological breakthroughs focus on efficient electrolysis and the construction of hydrogen transmission pipelines [12].

Energy storage is key to smart grid flexibility and stability, reshaping power systems via multi-dimensional regulation. Diverse technologies (e.g., lithium-ion batteries, compressed air storage) mitigate renewable intermittency and boost grid regulation [13]. In China, lithium dominates short-term use, while hydrogen storage becomes cost-competitive long-term. The recent PLFC-ADP algorithm enhances multi-battery efficiency by balancing scheduling and battery degradation. Digital twin-multi-agent reinforcement learning (MARL) optimizes real-time control and disaster resilience. Blockchain/IoT-based "shared energy storage" integrates decentralized resources, raising utilization by 28.3% [14,15].

3.3 Demand-Side Response

Demand-side response is one of the core technologies of smart grids, aiming to guide users to dynamically adjust their electricity consumption behavior through economic incentives or price signals, optimize the supply and demand balance of the power system, and enhance the flexibility of the power grid and the capacity to accommodate renewable energy [14]. Its principle is based on the "source-load" collaborative dispatching. Through real-time data interaction with intelligent terminals (such as energy management systems and smart meters), it realizes the active regulation or transfer of load, reducing the reliance on traditional peak shaving units. The main features include:

Real-time performance. Relying on Internet of Things (IoT) technology to achieve second-level responses, for example, the Zhangjiagang Free Trade Zone in Jiangsu Province reduced the load by 558,000 kilowatts within one second through an automatic demand response system.

Interactivity. Users participate in power dispatching through market trading platforms. For example, the DRAP project in California, the United States, allows users to obtain economic returns. Flexibility. It covers multiple types of load resources such as industry, energy storage, and electric vehicles (EVs), and supports bidirectional regulation of "peak shaving and valley filling" [16,17].

Its working principle is shown in Figure 5:

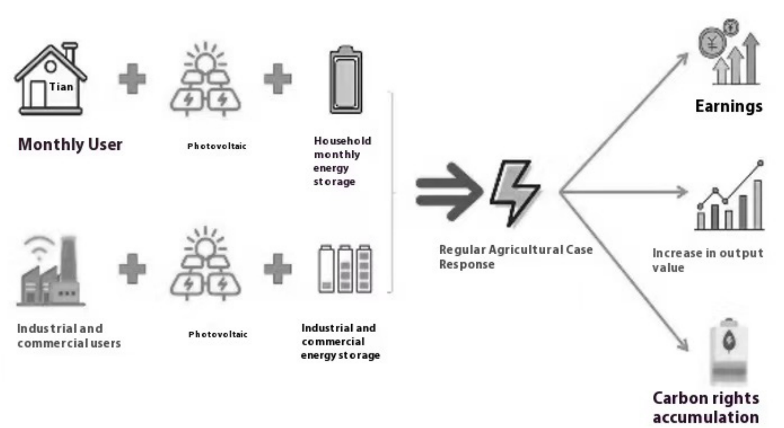

Fig.5 Demand Side Response Schematic

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According to the implementation mechanism and technical path, the current demand-side response can be classified into the following three categories:

Market-based responses based on prices: including time-of-use electricity prices, bidding models, etc. For example, Jiangsu Province first introduced the demand-side bidding mechanism in 2018, where users independently declared the load and incentive prices. 2. Automatic Demand Response (ADR): International standards (such as OpenADR2.0) are adopted to achieve automatic signal transmission and control. In Japan, the ADR system is used to trigger energy-saving responses in households and enterprises during power shortages. 3. Renewable energy collaborative response: By aggregating distributed energy sources (such as EVs and energy storage) to participate in grid frequency regulation, the efficiency of new energy consumption is enhanced. Shanghai and other places have piloted the inclusion of charging piles and microgrids in the response resource pool [18,19].

3.4 Virtual Power Plants

A virtual power plant is an energy management system that aggregates distributed power sources, energy storage devices and adjustable loads (such as electric vehicles and industrial loads) through digital technology. The core principle is to achieve the coordinated optimization of decentralized resources through intelligent algorithms and communication technologies, participate in power market transactions or power grid dispatching, thereby enhancing energy utilization efficiency and system stability. It can dynamically respond to the demands of the power grid, regulate the balance between supply and demand, and also integrate micro and small resources to form large-scale regulation capabilities. In terms of intelligence, real-time control is achieved by relying on technologies such as cloud computing and AI [20]. In addition, it can also participate in power trading as an independent entity and obtain profits.

At present, the working framework of the virtual power plant is shown in Figure 6:

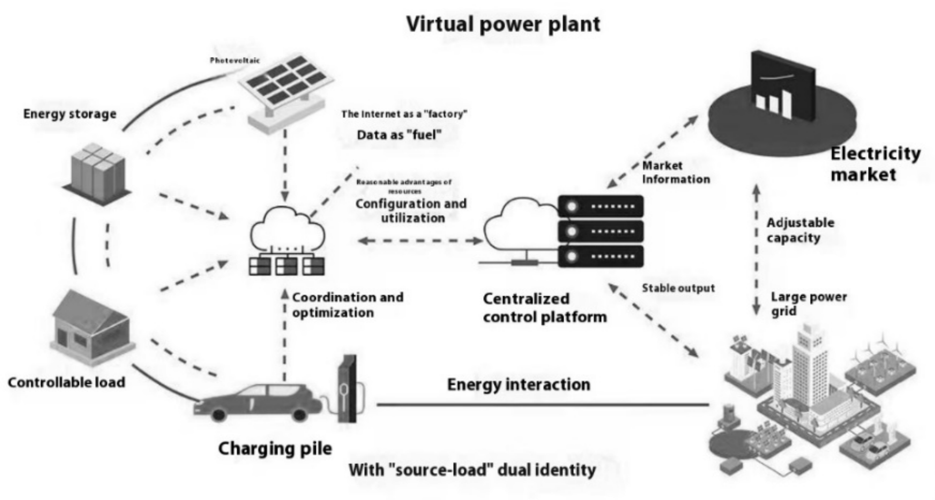

Fig.6 Virtual Power Plant Schematic

At present, the development stages of virtual power plants worldwide can be divided into three categories:

Invitation stage: Mainly policy-based demand response, relying on government subsidies. Typical cases such as Jiangsu and Shanghai have achieved peak shaving and valley filling through the time-of-use electricity price mechanism. Market-oriented stage: Gain profits through market-based transactions, such as the Guangdong Yue Neng Tou platform integrating energy storage, charging piles and other resources, achieving second-level frequency regulation response and participating in the spot market. Autonomous scheduling stage: Cross-regional transactions are achieved in mature markets, and users become "prosumers", such as the EU FENIX project exploring the autonomous coordination of distributed energy [21].

In China, virtual power plants are still mainly load-bearing type. Pilot projects in places such as Shanxi and Guangdong have exceeded the scale of one million kilowatts, but they generally face challenges such as the lack of technical standards and the imperfect market mechanism [21,22].

Demand-side response combined with virtual power plants can enhance the observability, measuability and controllability of the power system. It supports new energy-centric grid transitions without compromising stability or requiring additional infrastructure. VPPs reshape grid operations through integrated resource aggregation—

combining users, renewables, and storage—to form flexible “load-type” or “source-grid-load-storage” systems. They balance supply-demand dynamics by aggregating demand-side flexibility, optimizing load management, and mitigating peak shortages. Additionally, VPPs boost green energy adoption by coordinating source-grid-load-storage interactions to increase renewable utilization via market participation or valley-filling responses. Advanced digital technologies enable precise resource monitoring and intelligent scheduling, strengthening demand-side responsiveness and interactivity [22].

3.5 Typical Demonstration Projects of Smart Grids

This article selects the State Grid Shanxi Electric Power Company of China as an example for analysis. Since 2022, State Grid Corporation of China has been committed to promoting the digital transformation strategy of the power grid. Shanxi Power Grid, a branch of State Grid Electric Power, has carried out the construction of a digital audit information system, which can explore the impact on the power consumption of the power grid under the prescribed conditions.

Under the influence of the digital background, Shanxi Power is of a very large scale, involving support from multiple fields and parties, and the technologies involved are also very complex. For instance, Shanxi Electric Power has been actively exploring new models for data management and auditing in power grid enterprises. Firstly, it has conducted a comprehensive review of its internal data and meticulously classified it into three major categories: basic data, business data, and financial data. Among them, the basic data covers basic information such as the power grid architecture, equipment ledgers, and user files; Business data encompasses the data generated in operational links such as power production, dispatching, and marketing. Financial data includes economic data such as cost accounting and revenue statistics.

On this basis, Shanxi Electric Power began to design and construct an audit data mart to provide strong data support for internal audit work. This data mart is structurally divided into two data levels: the provincial company headquarters and the directly affiliated units. The provincial company headquarters level gathers the aggregated data and key indicators of the provincial power grid business, which is used to support the audit analysis at the strategic level. The level of the directly affiliated units focuses on the detailed business data of each grassroots unit, facilitating targeted audit supervision and achieving in-depth control over business details.

3.6 Challenges Faced by Smart Grids

The security risks of Internet of Things (iot) terminals are on the rise: With the acceleration of the intelligentization process in the power industry, the application of various iot intelligent terminals in the power system has seen explosive growth. It is estimated that by 2025, the number of Internet of Things (iot) smart terminals deployed in the power system will reach as high as one billion. Such a huge number of terminal accesses and frequent data interactions have greatly expanded the attack surface of power grid security risks. Once there are security vulnerabilities in terminal devices or data links, it is highly likely to bring unpredictable and serious consequences to the stable operation of the power grid, and may even trigger a chain reaction, threatening the security of the entire power system.

Risks of the „legalization“ utilization of user privacy data: The advent of the big data era has blurred the boundaries of personal privacy rights. A large amount of private information such as users‘ electricity consumption data holds huge commercial value, which makes it possible for power enterprises or third parties (such as insurance companies, electrical appliance manufacturers, etc.) to utilize these data in accordance with the law to achieve the mining of commercial interests. Although such utilization may be carried out within the legal framework, it undoubtedly intensifies the risks to users‘ privacy rights and interests, and the security of users‘ personal information is facing unprecedented challenges.

Highly destructive targeted cyber attack threats: As a key strategic asset of the country, power infrastructure has now become a key target of attacks by hostile countries or terrorists. The government‘s high reliance on power infrastructure has exposed the power network to the risk of targeted cyber attacks from the outside. Attackers often conduct in-depth research on the design and operation vulnerabilities of power systems and launch attacks using specially customized viruses, Trojans and other malicious programs, aiming to cause large-scale power outages or severe damage to key power facilities. Their potential destructive power should not be underestimated. Once successful, it will have a disastrous impact on the national economy, social order and people‘s lives.

3.6.1 Operational effects and optimizable items

The current proportion of new and old energy sources in China is shown in Figure 7.

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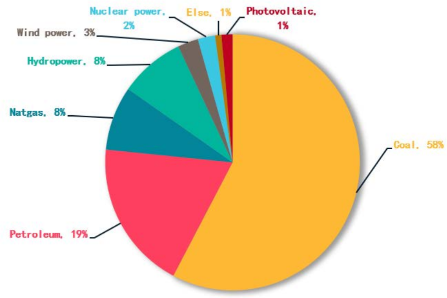

Fig.7 China's share of energy sources

To meet diversified electricity demands and optimize resource allocation, it is necessary to break through the traditional power transmission mode and adopt long-distance AC/DC hybrid transmission technology to achieve cross-regional power dispatching. However, the expansion of power grid scale and the complexity of its structure have exacerbated safety risks: large-scale interconnected systems are prone to causing safety hazards due to local configuration imbalances, and the technical characteristics of AC/DC hybrid transmission may interfere with line operation and relay protection, affecting system stability.

At the distribution network level, the current one-way transmission mode leads to a lack of interaction between users and the power grid, significant peak-valley load differences, low power consumption efficiency, resulting in resource waste and rising investment costs. To this end, it is necessary to build an intelligent two-way interactive system: through the collaboration between the power grid and the user end, guide the demand response and enhance the consumption capacity of distributed power sources, and simultaneously optimize the distribution protection technology to adapt to the new operation mode. Meanwhile, industry organizations need to jointly formulate unified technical standards, covering key areas such as communication protocols and data interfaces, in order to enhance device interoperability and reduce integration costs.

For the construction of microgrids, a modular design concept should be adopted to build an expandable network topology structure. Flexible upgrades should be achieved through the division of independent functional modules, and standardized interfaces and communication protocols should be reserved to ensure compatibility and interconnection with the smart grid system. This system provides technical support for building a new type of efficient and low-carbon power system through the coordinated optimization of power sources, grids, loads and storage.

4. Conclusion

Digitalization is the core technical support for the intelligent upgrade of the power system. It is necessary to build a future power system empowered by digitalization and intelligence by optimizing the network layout, promoting the intelligent transformation of equipment and information construction.

In the design of renewable energy microgrids, it is necessary to comprehensively consider resource endowments, market demands and policy environments. Based on the efficient development and utilization of renewable energy, technological innovation and system optimization should be taken into account. On the one hand, the efficiency and reliability of power generation technology should be enhanced; on the other hand, the stability of system operation should be strengthened through architecture optimization. Meanwhile, policy support and international cooperation are the key driving forces for achieving sustainable development.

The development of smart grids is confronted with challenges such as technological breakthroughs and high investment. It is necessary to make simultaneous efforts in both hard technology research and development (such as enhancing system self-healing, integration, and security performance) and soft science research (strategic planning, market mechanisms, and policy adaptation). Industry practitioners should rely on the characteristics of smart grids, take upholding principles and innovation as the guiding principle, and continuously improve system functions through breakthroughs in key technologies and original innovations, ultimately achieving a comprehensive enhancement in the safety, reliability and economy of grid operation.

Authors Contribution

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

References

[1] Li Liang, Yuan Jingjing. Technical Analysis of New Energy Photovoltaic Power Station Access to Distribution Network. Lamps & Lighting, 2025, (02):124-126.

[2] Zhang Kaiming. Research on MPPT and Energy Storage Control Strategy of Wind-solar Hybrid Power Generation System. Harbin: Northeast Agricultural University, 2023.

[3] Ding Qian. The Application of Distributed Energy and Energy Storage Technology in Smart Grid Construction. Lamps & Lighting, 2025, (02):234-236.

[4] Guo Qiancheng. Research on the Power Loss Analysis Method of Photovoltaic Power Stations Based on Smart Grid. Lamps & Lighting, 2024, (11):126-128.

[5] Cao Zhengfei, Zhang Zhenxing, Wang Linna, et al. Analysis of the Impact of Distributed Photovoltaic Access on the Regulation and Operation of Power Grids. China Plant Engineering, 2024, (23):101-103.
[6] Liu Yongdi. Research on the Impact of Wind Power Generation on the Power Grid. Wisdom China, 2024, (05):78-79.
[7] Li Sarengaowa, Yuan Xin, Chen Heng, et al. Introduction of Compressed Air Energy Storage Technology and Prediction of Key Development Directions. Energy Science and Technology, 2024, 22(06):56-60.
[8] Zhao Xingzhu, Yin Changyong. The Development of Renewable Energy Power Generation Systems and the Application of Grid Connection Technologies. Journal of Shandong Industrial Technology, 2017, (20):184+246.
[9] Zhang Dong, Feng Kaihui, Shi Zhiyong, et al. The Current Situation and Suggestions of Grid Connection Development of New Energy in China. Solar Energy, 2024, (07):89-97.
[10] Shi Wenhui, Qu Jixian, Luo Kui, et al. Grid-Integration and Operation of High-Proportioned New Energy. Strategic Study of CAE, 2022, 24(06):52-63.
[11] Li Guoping. Research on Key Technologies of Electrical Automation in the Grid Connection of Renewable Energy. Petrochemical Industry Technology, 2024, 31(11):154-156.
[12] SINNEH-SINNEH, IBRAHIM, et al. Integration of Digital Twin-Based Control of Smart Nano Grids and Multiagent Reinforcement Learning for Resilient Energy Management. SSRN, 2025.
[13] Su Nan. Energy Storage has evolved from a "Minor Supporting role" to a "Major Player".2025.3, quoted on April 29th, paper.people.com.cn/zgnyb/pc/content/202503/03/content_30060773.
[14] Xue X, Ai X, et al. Continuous Approximate Dynamic Programming Algorithm to Promote Multiple Battery Energy Storage Lifespan Benefit in Real-time Scheduling. IEEE, 2024.
[15] Zhang Qiang. Prospects for the Energy Storage Technology Route of China's Power System Oriented towards Carbon Neutrality. Technology Review for Carbon Neutrality, 2025.
[16] Guo Pingping, Yang Di, Chen Chen, et al. The Current Situation and Development Suggestions of Power Demand Response in China. 2020.08, quoted on April 29th.
https://news.bjx.com.cn/html/20200810/1095674.shtml
[17] Drishya Manohar. Smart Grids: Revolutionizing Intelligent Energy Management. Cavli Wireless, 2025.
[18] Vaidya S, Prasad K, Kilby J. The Role of Multilevel Inverters in Mitigating Harmonics and Improving Power Quality in Renewable-Powered Smart Grids: A Comprehensive Review. Energies 2025, 2025.
[19] T. A. Rajaperumal, C. Columbus, et al. Transforming the electrical grid: the role of AI in advancing smart, sustainable, and secure energy systems. Energy Informatics, 2025.
[20] Cheng Huanyu, Xu Xiangmin, Guo Fengfeng, et al. Research on the Normal Operation of Virtual Power Plants in the field of building Air Conditioning. Coal Economic Research, 2024, 44(08):38-43.
[21] Electricity Roundtable. Research on the Regular Operation Mechanism of Regional Virtual Power Plants in China Southern Power Grid in 2024. 2024.08, quoted on April 29th.
http://www.nrdc.cn/information/informationinfo?id=377&cook=2.
[22] Kang Yilong, Chen Chen, Guo Fei, et al. Research on Quality Capability Evaluation of Project Participants in the Digital Context—A Case Study of Large-Scale Power Grid Infrastructure Projects. Price:Theory & Practice. 2024, (06):129-134.