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Analysis of Key Smart Grid Technologies and Wind–Solar–Storage Applications under Distributed Energy Integration

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Abstract. As renewable energy resources continue to be deployed on a larger scale, integrating distributed generation into smart-grid environments has become an increasingly important aspect of modern power system development. This paper focuses on the major issues encountered during the grid connection of distributed energy resources. First, the core technologies related to grid-connected control, energy management, state perception, and fault diagnosis are systematically reviewed. Then, a wind-solar-storage complementary energy system is selected as a typical application scenario, which is used to investigate the engineering implementation of these technologies and examine the operational performance and collaborative mechanisms of the system through specific case studies. The analysis shows that grid-connected control supports stable renewable energy integration, while energy management strategies facilitate coordination among wind generation, photovoltaic resources and energy storage units. Overall, these technologies have different functions and focusses, but they are closely related in practical applications, which together raise the operating efficiency and reliability of distributed energy systems. This research helps to understand the problems of smart grid technology, engineering application analysis, and subsequent collaborative optimisation research involved in distributed energy access.

Keywords: Distributed energy resources, Smart grid, Grid-connected control, Energy management, Wind–solar–storage system

1. Introduction

Global power systems are moving toward a structure in which renewable and distributed resources occupy a larger share of electricity supply. Driven by the national dual-carbon strategy, renewable and distributed energy resources, especially wind and photovoltaic power, have expanded rapidly and now play an increasingly important role in electricity supply. The development of this kind of energy can not only help the whole energy industry transform into a green and low-carbon direction, but also open up new opportunities for the evolution of smart grids. However, unlike conventional units, wind and photovoltaic outputs vary with weather conditions, which makes their grid behavior less predictable. When renewable resources account for a large share of grid-connected generation, problems such as voltage fluctuation and power imbalance may occur [1].

The number of users connected to the power grid continues to grow, and the traditional one-way power supply mode is gradually transitioning to a multi-source power supply architecture. This

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change has greatly increased the complexity of system operation and brought challenges to scheduling control and fault disposal. Focussing on these problems, researchers worldwide have conducted extensive studies on grid control, energy management and state perception technologies. The wind-solar-storage multi-energy complementary system uses energy storage devices to reduce the power fluctuation of renewable generation output, thereby enhancing system flexibility and operational stability. Moreover, the access of distributed power supply has also changed the original fault characteristics of the power system. Although the existing research has made a comprehensive analysis of fault positioning and fault diagnosis technologies, these technologies still suffer from insufficient positioning accuracy and real-time performance under complex operating conditions [2].

On the whole, the existing research has made progress in areas including grid control, energy management and fault diagnosis, and the academic community has also developed a variety of technical means to improve the renewable energy accommodation capability, system flexibility and operation reliability. However, as the share of distributed energy resources continues to rise, the problems of insufficient synergy between various technologies and weak overall optimisation ability of the system still exist.

Therefore, this paper adopts a combination of literature review and case analysis to carry out research on the key technologies of smart grids under the distributed energy access scenario. On the one hand, it sorts out the key technologies of grid control, energy management, state perception and fault diagnosis. Conversely, it selects a typical wind-solar-storage integrated energy system as a research case, and analyses the application, operation performance and collaborative operation mechanism of each technology in the actual engineering.

2. Key technologies for smart grids under distributed energy resource integration

2.1. Grid-connected control technologies for distributed energy resources

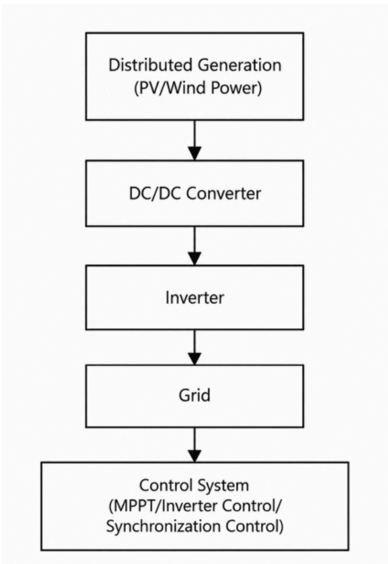

Figure 1. Structure of the distributed energy grid-connected control system

Picture credit: Original

As renewable energy installation increases, the grid-connected scale of distributed energy sources such as photovoltaics and wind power continues to expand. However, their output is strongly affected by external conditions, which may cause voltage and frequency instability and reduce power quality. In this context, for converter-based distributed generation, grid-connected control determines how the converter synchronizes with the grid, regulates active and reactive power, and responds to frequency or voltage deviations. Distributed energy is generally connected to the power grid through power electronic converters. Figure 1 shows the basic architecture of this grid-connected system.

As shown in Figure 1, the distributed power generation system will first complete the two tasks of voltage regulation and Maximum Power Point Tracking (MPPT) technique through the DC/DC converter, and then convert the direct current into alternating current that meets the grid standards by the grid-connected inverter. In the whole process, the grid-connected control system plays a core role. Through the regulation of voltage, frequency, active power and reactive power, the coordinated operation between distributed energy and the power grid can be realised [3].

The grid integration process of distributed energy resources currently mainly involves the following key control technologies:

(1) Maximum power point tracking technology (MPPT)

MPPT is widely used to increase the energy conversion efficiency of renewable generation systems. In photovoltaic applications, it achieves maximum power output by adjusting the working voltage or current; in the wind power system, it relies on speed or torque control to achieve the optimal capture of wind energy.

Typical MPPT approaches include the perturb-and-observe algorithm and the Incremental Conductance (INC) strategy, among which the tracking accuracy of Incremental Conductance (INC) Method under dynamic working conditions is usually higher than that of disturbance observation method [3]. The reasonable use of MPPT technology can not only improve the utilisation rate of renewable energy, but also create favourable conditions for the control and subsequent inverter operation.

(2) Grid-connected inverter control technology

The grid-connected inverter is the core interface equipment during the integration of distributed generation into the utility network. Its control characteristics have a direct influence on both power quality and overall system stability. At present, double closed-loop control is the most commonly used control architecture in grid-connection inverters. It consists of two parts: an outer voltage regulation loop and an inner current regulation loop, which can effectively improve the dynamic response ability and operation stability of the system, so it has been widely used in grid-connection inverters [1, 3].

In actual engineering, proportional integral (PI) control, sliding mode control and other methods are also often used to enhance the stability and anti-interference ability of the system [3]. At the same time, through the coordinated regulation of active power and reactive power, the voltage and frequency of the power grid can be accurately controlled to ensure the stable operation of the grid-connected system.

(3) Virtual synchronous generator control technology

Most distributed energy systems are integrated into the grid through converter-based interfaces, whose inertia-support capability is weak and may cause fluctuations in grid frequency. In recent years, the academic community has proposed a control method called the virtual synchronous generator approach (VSG). By simulating the dynamic behaviour of conventional synchronous generators, this control strategy enables the inverter to exhibit inertia and damping characteristics comparable to those of synchronous machines, thereby enhancing system dynamic stability [3, 4].

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The VSG control strategy is mainly composed of two parts: a virtual speed regulator and a virtual excitation controller. By establishing a correlation between frequency and power, voltage and reactive power, the dynamic adjustment of system frequency and voltage is completed. Under the scenario of high penetration of renewable energy, VSG technology has shown good stability and has now become one of the important research directions in the industry [4].

2.2. Smart grid energy management technology

After the stable grid integration of distributed energy, it is difficult to completely solve the problems of internal power fluctuations and energy distribution of the system by relying on grid-connected control technology alone. Therefore, it is necessary to use the energy management system to coordinate distributed generation resources, energy storage units and electrical loads to improve the efficiency of system operation.

The share of renewable resources such as wind and photovoltaic generation in modern power systems has been increasing. Their output is obviously variable and difficult to predict, which will aggravate the power fluctuation and load imbalance during grid operation [5]. To solve this problem, we must rely on the energy management system (EMS) to coordinate scheduling and integrate control of various energy sources, so as to ensure the power balance and economic operation of the system [6].

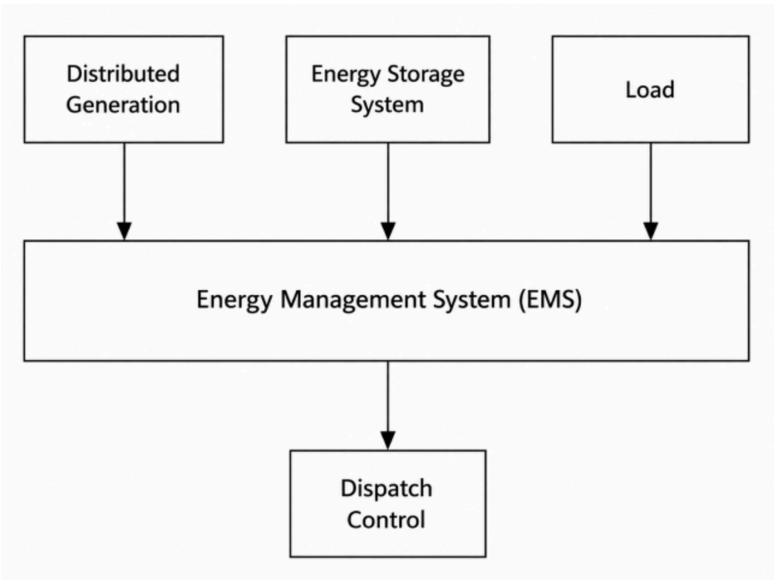

Figure 2. Structure of the smart grid energy management system

Picture credit: Original

As shown in Fig. 2, the energy management system plays the role of a core control unit in the smart grid. It can monitor the operation status of distributed power supply, energy storage system and load in real time. At the same time, it can combine load demand and electricity price information for unified scheduling and optimised control, and finally realise the rational distribution and efficient utilisation of electricity.

The energy management process of smart grids currently mainly involves the following key technologies:

(1) Coordinated source-grid-load-storage control strategy

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Source-grid-load-storage coordinated control can integrate the scheduling of power generation, energy storage, power grid and load resources to maintain supply-demand equilibrium, thereby increasing renewable energy utilisation and enhancing system flexibility [5].

(2) Energy storage scheduling and energy balancing technology

The energy storage system serves an essential function in smart-grid energy management. It is mainly used to reduce the output fluctuation of distributed energy and achieve peak shaving and energy balance [5]. When the power generation of distributed energy exceeds the electricity demand, the storage unit will switch to charging mode, and the stored electricity will be released at the peak time to maintain system power balance in this way. The energy storage system must meet the state-of-charge (SOC) constraints and the operation constraints of the equipment itself in the process of charging and discharging. With a reasonable scheduling strategy, it can both prolong equipment lifetime and lower overall operating costs.

(3) Intelligent scheduling technology based on optimization algorithms

Advances in intelligent algorithms have made optimisation-based energy management an active research topic. This method formulates energy management as a multi-objective optimisation task, and jointly optimise the operating cost and operation safety under the premise of meeting the power balance and equipment operation constraints [7]. At present, commonly used methods include fuzzy logic control, model prediction control, and optimisation scheduling methods based on reinforcement learning. Take reinforcement learning as an example, this energy management method can continue to learn in a complex dynamic environment, optimise the scheduling strategy through iteration, and improve the adaptability and operating efficiency of the system.

2.3. Grid state perception and fault diagnosis technology

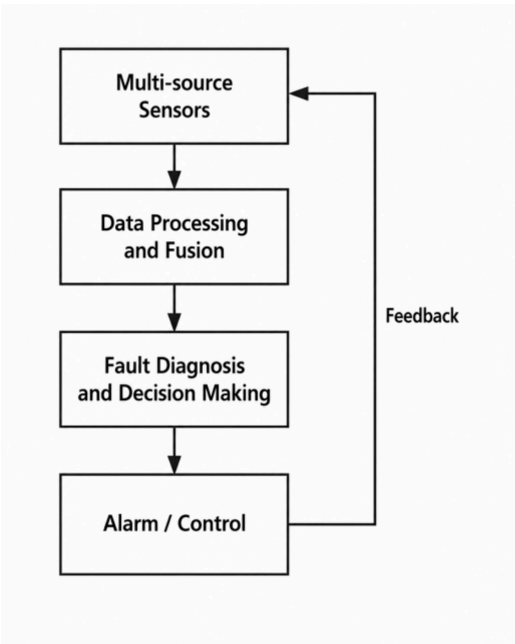

Figure 3. Structure of the grid state perception and fault diagnosis system

Picture credit: Original

As modern power systems continue to evolve, the operating environment of power grid equipment is becoming more and more complex. Conventional inspection and routine maintenance alone can no longer satisfy practical operational requirements, so it is necessary to introduce power grid status perception and fault diagnosis technology. This kind of technology can carry out real-time condition monitoring and intelligent assessment of grid operating status, and realise rapid identification and early warning of faults. It is generally believed in the industry that comprehensive and real-time monitoring of the operation status of power equipment is fundamental to maintaining secure system operation [6, 8]. At the same time, building an integrated state monitoring and fault diagnosis system can significantly enhance both the speed and accuracy of fault detection and improve the reliability of power grid operation.As shown in Fig. 3, the power grid status perception and fault diagnosis system is divided into three parts: data acquisition layer, data processing layer and intelligent decision-making layer. It relies on multi-source data collection, intelligent analysis and fault identification technology to realise all-round monitoring and intelligent fault diagnosis of the operation status of power grid equipment.

(1) Grid state perception technology

State perception provides the data foundation for condition-based maintenance by continuously collecting electrical, thermal and mechanical signals from key equipment. At present, power grid state perception mainly collects current, voltage, temperature, vibration, partial discharge and other sensing data [3]. Due to the continuous development of advanced sensing technology, optical fibre sensing, microelectromechanical system (MEMS) sensors and wireless sensing networks have been widely used in power grid status monitoring. The above technology can collect the key state parameters of the equipment with high accuracy, while improving the real-time and reliability of state perception.

(2) Multi-source data fusion and state evaluation technology

The operation of power grid equipment involves a number of physical quantities. It is difficult to fully reflect the health status of the equipment by relying on a single data source. Therefore, the status monitoring system needs to use multi-source data fusion technology to comprehensively analyse various data. In terms of data processing, the process mainly includes data preprocessing, feature extraction and information fusion. The system generally uses wavelet transformation, principal component analysis and other methods to extract key features, and then combines multi-modal data fusion methods to improve the accuracy of state evaluation [2].

On this basis, equipment health-state evaluation models can be established to classify operating conditions into normal, abnormal, and faulty states, thereby supporting subsequent fault diagnosis.

(3) Fault diagnosis and intelligent identification technology

After completing the monitoring of operating conditions through state perception technology, fault diagnosis technology can be further used to determine the fault type and locate the fault location, which is also one of the important application directions in this field. The development of artificial intelligence technology has gradually made data-driven fault diagnosis methods mainstream. According to the traditional methods of feature extraction and threshold judgement, the diagnostic accuracy is low and robustness is insufficient. Therefore, the current research uses more deep learning technologies such as convolutional neural networks (CNN) and long-term and short-term memory networks (LSTM) to automatically extract features from massive operating data to realise high-precision identification of complex faults [9].

For example, voltage and current data collected by phasor measurement units (PMUs) can be used to build fault-diagnosis models for rapid location and classification of grid faults, thereby significantly improving the efficiency of power grid fault handling [10].

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3. Application case analysis of key technologies in wind–solar–storage multi-energy complementary systems

3.1. Overview of wind–solar–storage multi-energy complementary systems

The integrated multi-energy system is composed of a renewable energy power generation unit, an energy storage system, a grid-connected transformer and an intelligent management module. Among them, wind turbine units are responsible for electrical power production, and the energy storage system is responsible for suppressing power fluctuations and maintaining power balance. This system combines the technologies of grid control, energy management and status monitoring to ensure that the power grid can maintain stable and efficient operation under complex working conditions.

3.2. Application cases of grid-connected control technology

Within a wind-solar-storage integrated energy system, the core role of grid-connected control technology is to allow renewable generation resources to be integrated into the utility network stably under the condition of output fluctuations and power grid disturbances, while maintaining the balance of voltage, frequency and power exchange. Shenzhen Houhai's grid-type windscape storage system is a typical case of the application of grid-connected control technology [11]. This system uses a grid-based energy storage transformer, so that the energy storage unit can actively establish voltage and frequency benchmarks, providing support when the power of renewable energy fluctuations or the power grid is disturbed, which has greatly improved grid stability.

Compared with traditional grid-following control, grid-following control performs better in the scenario of high penetration of renewable energy, which can enhance the anti-disturbance ability and operation reliability of the system. The intelligent micro-grid project of Shuiguang storage in Shixian County, Hebei Province is another typical case. It achieves multi-energy integrated operation through collaborative control of hydropower, photovoltaic and energy storage systems. In grid-connected mode, the system can adjust the voltage and frequency of the power grid, and can maintain independent and stable operation after switching to off-grid mode [12]. This reflects that grid-connected control technology has developed from simple access control in the past to a comprehensive control system with both power grid support capacity and off-grid seamless switching ability.

In terms of control strategies, the aforementioned systems generally adopt a coordinated structure comprising wind and photovoltaic generation units, storage-support components, and inverter control modules. Wind and photovoltaic units use MPPT strategies to maintain optimal power output, while energy storage units primarily serve to smooth power fluctuations and provide dynamic support. Meanwhile, inverters employ double closed-loop control to regulate grid-connected currents precisely.

In addition, under the scenario of improving the penetration rate of high renewable energy, network-based control has obvious advantages in improving system adaptability. Therefore, the future grid-connected control strategy should not only take into account the efficiency of electricity conversion, but also strengthen the power grid support capacity and system operation stability.

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3.3. Application cases of energy management technology

The energy management technology in a wind-solar-storage integrated energy system mainly coordinates the operation of different energy units, including wind generation, solar generation and energy storage resources, to achieve power balance and improve economic performance. The integrated wind-solar-storage-charging microgrid project in Wuhu, Anhui Province, is a representative application of this technology. The project is equipped with a 14.85 kW photovoltaic system and a 100 kW/200 kWh energy storage unit. Through an Energy Management System (EMS), the operational condition of each subsystem can be tracked in real time, and the charging and discharging schedules for the storage system can be adjusted according to load demand. In this case, storage dispatch reduces the mismatch between photovoltaic output and charging demand, while EMS-based control keeps the microgrid operating within a more stable power balance range [13].

When the system is running, it will give priority to photovoltaic power generation to supply the local load. Once the power generation exceeds local demand, the EMS will store surplus electricity in the energy storage system; on the other hand, when the electricity consumption peak or the photovoltaic output is insufficient, the storage system will discharge stored energy to compensate for the deficit. In this way, we can realise peaking and filling and maintaining power balance. Studies have shown that reasonable energy management strategies can increase the load matching ability of the system, and the utilisation rate of renewable energy will also improve [14].

In multi-energy complementary systems such as hydro-solar-storage systems, energy management technology is generally used with the optimisation scheduling model. The wind-solar-storage system generally adopts a prediction-based optimisation method for energy management. It first predicts wind speed, light intensity and load demand, obtains the short-term power change trend, and then formulates the charging-discharging schedule of energy storage and the generation schedule of various power supplies through optimisation algorithms, so that the overall system operating cost can be reduced while operational stability is improved. Existing research shows that scientific energy storage scheduling strategies can effectively reduce renewable energy curtailment, while improving the economic benefits and flexibility of the system [15].

The results suggest that energy management technology has gradually shifted from the control of a single device in the past to the collaborative optimisation of the whole system. Although the technical schemes used in these two types of application scenarios are different, the core is to strengthen the cooperation between generation resources, storage facilities and load-side demand. This also reflects that the operation effect of distributed energy systems increasingly depends on the overall scheduling level, rather than the performance of a single device. Therefore, intelligent and adaptive energy management strategies will play a significant role in future smart-grid development.

3.4. Application analysis of state perception and fault diagnosis technologies

The number of renewable energy equipment is increasing, and the system architecture is becoming more and more complex. State perception and fault diagnosis technology is widely used in real-time monitoring and assessment of system operating conditions to support secure and stable grid operation. Take the wind-solar-storage system as an example, the monitoring objects mainly include photovoltaic modules, wind generator sets, energy storage batteries and grid-connected inverters. The system collects operating data through voltage, current, temperature and other sensors, and then uploads it to the monitoring platform for comprehensive analysis. Studies have shown that multi-

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source data acquisition and fusion technology can improve the accuracy of equipment status recognition and provide reliable support for later fault diagnosis.

In complex multi-energy systems, fault diagnosis technology is moving towards intelligence step by step. Machine learning and deep learning algorithms can process a large amount of running data and automatically identify complex faults. Relevant research also shows that training neural network algorithms through power grid operation data can significantly improve the accuracy of fault classification and positioning, and the level of system operation and maintenance has also been strengthened [7, 9].

3.5. Comparative analysis of comprehensive case study results

This study analyzed application cases of grid-connected control technology, energy management technology, state perception technology, and fault diagnosis technology in wind-solar-storage integrated energy systems. The results indicate that these technologies play distinct roles in system operation and jointly contribute to overall system performance through coordinated interactions.

In terms of function, grid-connected control technology is mainly to ensure that renewable generation resources can be integrated into the grid in a stable manner. Energy management technology is responsible for the unified scheduling and coordinated control of wind generation, solar generation and energy storage resources, thereby achieving optimal power balance and operational efficiency. State perception and fault diagnosis technology can ensure secure system operation and improve the efficiency of operation and maintenance through real-time monitoring and assessment of equipment operating conditions. These three types of technologies have clear layers and complementary functions in the system.

Judging from the actual operation effect, grid-connection control technology can significantly weaken the voltage fluctuations and transient shocks brought about by renewable energy grid-connection, and improve the power quality. Energy management technology balances the output fluctuations of renewable energy by optimising scheduling, making load matching better. For state perception and fault diagnosis technology, it can quickly identify faults, issue early warnings, reduce fault-handling time and enhance overall system reliability. Table 1 compares and analyses their application in the wind-solar-storage system.

Table 1. Comparative analysis of key technologies in wind–solar–storage systems

Technology type	Primary function	Key technologies	Application effects
Grid-connected control technology	Achieve stable integration of renewable energy sources	Double closed-loop control, MPPT, grid-forming control	Improve grid integration stability and power quality
Energy management technology	Achieve coordinated scheduling of multiple energy sources	EMS, optimal scheduling algorithms, energy storage control	Mitigate power fluctuations and improve renewable energy utilization
State perception and fault diagnosis technology	Achieve operating state monitoring and fault early warning	Multi-source sensing, data fusion, intelligent diagnosis	Improve system reliability and reduce operation and maintenance risks

The analysis indicates that within a wind–solar–storage integrated system, these three types of technologies do not operate independently, but form a collaborative system integrating control, scheduling and perception. Specifically, grid-forming control is the basis for the stable operation of the system. Energy management technology plays the core role of system optimisation and scheduling. State perception and fault diagnosis technology provides important support for the operation of the whole system by providing real-time operation data and ensuring operation safety. The cooperation of various technologies has jointly built the main technical architecture for the efficient operation of distributed energy under the smart grid. Therefore, the development of intelligent power grids in the future should not only develop the research of single technologies, but also pay attention to the integration and coordination of various technologies.

4. Challenges and future development directions

The grid-connected scale of distributed renewable resources, including wind and photovoltaic generation, continues to expand, and the operation of smart grids is also facing new challenges. The output of wind power and photovoltaics is naturally intermittent and random, and high renewable penetration places greater demands on system regulation capability. For grid-connected control, the traditional network-type control is highly dependent on power grid conditions, and the stability of operation in a weak power grid environment is easily affected. Although network-based control has shown good application prospects, multi-device collaborative control still needs to be studied in depth. In the field of energy management, the prediction error of wind speed and light intensity will reduce the accuracy of scheduling results. Coupled with the high computational complexity of the multi-target optimisation model, satisfying real-time operational requirements remains challenging. In state perception and fault diagnosis, the quality of sensing data and the ability to integrate information still need to be improved, and there is also a lot of room for optimisation for diagnostic accuracy and reliability under complex fault scenarios.

In the future, the development of smart grids needs to further integrate the technologies of grid-connected control, energy management, state perception and fault diagnosis to comprehensively improve the operating efficiency and overall system stability. Meanwhile, we should also develop renewable energy power prediction, network-based control, intelligent fault diagnosis and other technologies to provide technical guarantee for large-scale renewable energy integration and secure smart-grid operation.

5. Conclusion

This paper examines how grid-connected control, energy management, state perception, and fault diagnosis technologies are deployed in smart grids with high shares of distributed energy resources. Drawing on both theoretical analysis and a practical case study of a wind-solar-storage integrated energy system, this paper clarifies how these tools underpin the reliable and efficient operation of modern power systems. This requirement becomes increasingly critical as renewable penetration rises. Grid operators now face the core challenge of balancing system stability and energy utilization.Therefore, a coordinated understanding of these technologies is necessary for evaluating their practical value in distributed energy integration.

The results show that grid-connected control helps renewable energy resources achieve stable grid integration. Energy management technology supports the coordinated operation of wind generation, solar generation and energy storage facilities. State perception and fault diagnosis technologies improve system monitoring and help ensure safe operation. Together, these technologies provide essential support for improving the performance of distributed energy systems.

The case study further highlights that wind-solar-storage configurations not only boost renewable utilization and power quality but also elevate overall system reliability, underscoring how these technologies work in tandem rather than in isolation. Stable grid operation relies not on any single

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tool, but on the seamless coordination of control, scheduling, monitoring, and fault diagnosis functions.

Although significant progress has been achieved, challenges related to renewable energy uncertainty, energy storage scheduling, and intelligent fault diagnosis still remain. Future studies should focus less on isolated technical modules and more on system-level coordination, especially under uncertain renewable output, variable load demand and complex fault conditions.

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