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Research on Coordinated Control Methods for Renewable Energy Grid Integration Based on Flexible Interconnection

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Abstract. In the context of harmonizing environmental protection and pollution control requirements, conventional power grids necessitate increased energy and resource consumption, which imposes higher demands on energy utilization. Consequently, flexible interconnection technologies for grid integration of new energy systems have become increasingly imperative. However, in the flexible interconnection new energy grid-connection structure system, the local control of the flexible interconnection device relies on rapid response logic, and the coordination between new energy and energy storage systems focuses on smoothing output fluctuations. Combined with long-term output prediction and optimized dispatching strategies, the power of new energy can be more stably integrated into the power grid. This paper conducts a comprehensive analysis of flexible interconnected power control strategies, categorizing application scenarios for hybrid distributed and centralized renewable energy systems. It adopts a hierarchical power allocation framework and an energy management strategy centered on optimizing energy utilization. While prioritizing the consumption of renewable energy generation and ensuring system stability, the study elucidates the synergistic logic among various components. This provides a practical approach for the efficient grid integration of diverse renewable energy sources, offering substantial significance for enhancing system stability and renewable energy utilization efficiency.

Keywords: Renewable energy grid integration, flexible interconnection, flexible devices, coordinated control

1. Introduction

Traditional power grids primarily rely on rigid power transmission and fossil energy. During the power-generation process, they release a large amount of pollutants such as CO_2 and SO_2, which exacerbate climate change and air pollution. Due to their limited capacity to integrate new energy sources with high volatility and intermittency, issues like voltage fluctuations and frequency instability are likely to occur, restricting the consumption efficiency of new energy. Moreover, malfunctions in large-scale power plants or main transmission lines may lead to widespread power outages, and the risks are even higher under adverse weather conditions and natural disasters such as hurricanes and hailstorms. A typical incident involving a centralized traditional power grid was the

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2003 Northeast blackout in the United States and Canada, which affected 50 million people. Therefore, traditional control methods cannot meet the requirements for real-time response and flexible adjustment among new energy sources, the power grid, and loads, and to some extent, they impact the safe and stable operation of the power system [1].

Within this context, the research process concerning interconnected systems and renewable energy grid integration structures unfolds as follows: First, the fundamental equipment involved in flexible interconnection is elaborated, clarifying its diverse design types, specific installation locations, and respective functions. Building upon this foundation, the implementation conditions, methods, and processes of interconnection devices are further analyzed, exploring their stabilization mechanisms and supportive roles within the system, while comparing system changes and adaptations before and after the integration of energy storage systems. Subsequently, the significance of distributed generation and centralized generation for flexible interconnection equipment is explained, with a focused discussion on achieving dynamic power balance among renewable energy generation units, flexible interconnection devices, energy storage systems, and loads. Finally, the importance of energy storage systems and their operational modes within flexible grid integration structures is elucidated, along with an exploration of future development directions in related fields.

To meet the demands of the contemporary transformation of new energy power grids, it is first necessary to understand that the large-scale integration of new energy into the grid also has certain limitations. In new energy power grids, the influence characteristics and control objectives of distributed power sources, energy storage, and loads vary significantly, and traditional centralized methods cannot achieve efficient control and coordination. Therefore, against this backdrop, the rapid adaptive capabilities of flexible devices and the interconnection and collaboration of new energy power grids are more prominent. They can better interconnect and coordinate the system, and at the same time provide underlying support for the development of new power systems and energy transformation.

2. System architecture and core control principles

2.1. Overview of the system architecture model

In the new energy grid-connected system, the overall configuration model of the flexible interconnection system is based on power electronic equipment as the hardware foundation. It achieves hierarchical connection through a physical structure of "new energy side access layer - flexible interconnection core layer - grid side connection layer", integrating multiple functions. This system is applied in scenarios such as distributed new energy grid connection, large-scale new energy base power transmission, and coordinated operation of multiple microgrids. Ultimately, it realizes flexible interaction and efficient operation between new energy and the grid through the hardware coordination among "power sources, grids, loads, and energy storage", providing support for the stable operation of high-proportion new energy power systems.

2.2. Flexible interconnection architecture in renewable energy grid integration systems

Distributed access units play a pivotal role in standardizing power characteristics, enhancing power generation efficiency, ensuring system security, and converting renewable energy into standardized electrical power. This provides the foundational infrastructure for enabling flexible aggregation of distributed energy resources. The new energy access layer is the node that connects distributed new

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energy sources to the entire system, adapting and optimizing the power characteristics of different new energy devices. Due to its maximum power point tracking function, it maintains efficient power generation by real-time monitoring and dynamic adjustment of power generation equipment. To further meet the distribution characteristics of new energy sources being "dispersed and small-scale" a modular design is adopted, meaning that the power of a single unit matches that of small new energy devices. If a unit fails, it will only affect the corresponding small range of equipment, further enhancing the system's fault tolerance [2]. To achieve a local small cycle of "power source - energy storage - load", starting from the principle of compatibility with small energy storage devices and micro power consumption devices, the system's adaptability to various devices is enhanced.

The aggregation stage plays a pivotal role in connecting the distributed access units with the core layer by concentrating decentralized power, unifying the form of electrical energy, flexibly adapting to scale, and providing basic monitoring and protection. With the increasing proportion of distributed new energy and the growing application of energy storage and micro-load devices, the adaptability and flexibility of distributed access units will become even more crucial. The technological optimization and functional expansion of these units may be the key to enhancing the stability and economy of the system. It makes the scattered new energy power more stable and easier to handle, laying a foundation for its subsequent smooth entry into the flexible interconnection core layer and achieving grid connection [3].

2.3. Flexible interface

In flexible interconnection systems for renewable energy grid integration, the flexible power interface serves as a critical component, undertaking the core function of interconnecting energy storage systems, renewable power generation equipment, the grid, and diversified loads. During charging operations, it efficiently transmits external electrical energy to the energy storage system; during discharging, it promptly feeds the stored energy back to the grid or load terminals, thereby facilitating flexible bidirectional energy flow within the system. Furthermore, the flexible interface features millisecond-level dynamic response capabilities, enabling rapid switching between charging and discharging states [4]. This aligns closely with the fast power regulation characteristics of energy storage systems, effectively mitigating the volatility and intermittency associated with renewable energy generation. From a safety perspective, the interface integrates multiple protection mechanisms—including overvoltage, overcurrent, and short-circuit protections—which allow for immediate interruption of energy transmission during faults. This prevents localized failures from propagating to the energy storage system or main grid, ensuring overall system stability and secure operation.

The electricity output by energy storage systems, the electricity generated by new energy sources, the grid connection standards, and the electricity demands of loads are often different. Therefore, the flexible interface must first address the issue of mismatched forms and parameters of electrical energy. Power electronic conversion circuits transform one form of electricity into another while adjusting parameters such as voltage and current, ensuring smooth energy transfer between energy storage, new energy sources, the grid, and loads without fluctuations due to form or parameter issues [5]. During energy storage charging, the alternating current from new energy sources or the grid is converted into direct current that can be used by energy storage devices; during energy storage discharging, the direct current is converted into alternating current that meets the requirements of the grid or loads, thus ensuring smooth bidirectional energy flow.

The terminal that executes control instructions is often the core of a system. In the process of receiving real-time dispatch signals, adjusting conversion efficiency and output power, it precisely

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controls the charging and discharging rhythm of the energy storage system. When there is an excess of new energy generation, it increases the charging power to store more electricity; when generation is insufficient, it boosts the discharging power to make up for the power shortage, maintaining the power balance of the system and ensuring that charging and discharging are in real-time alignment with system demands, thus avoiding power supply and demand imbalances.

The design and operation of energy storage system flexible interfaces must be constructed around three core objectives: "efficiency prioritization, coordinated synergy, and seamless switching." [6]. By optimizing circuit topology and employing high-performance power devices, energy conversion losses are reduced at the source. This serves not only as a fundamental prerequisite for enhancing the economic viability of energy storage systems but also as a critical foundation for maximizing the utilization efficiency of renewable energy integration.A comprehensive real-time monitoring mechanism—encompassing renewable power output fluctuations, grid frequency and voltage deviations, the operational status of the storage system itself, and load demand variations—enables precise regulation of conversion parameters through dynamic data-driven control.This ensures stability throughout the energy transfer process and effectively mitigates various risks. During mode transitions, particularly between grid-connected and islanded states, the flexible interface must demonstrate rapid mode identification and adaptive operational logic adjustment. The primary goal is to guarantee an uninterrupted power supply to critical loads, preventing any disruptions or fluctuations during switching from affecting end-users. Ultimately, this results in an integrated operational capability characterized by "high-efficiency conversion, dynamic coordination, and smooth transition."

With the increasing proportion of renewable energy integration, the power grid's demand for "flexible regulation" and "security and stability" continues to grow, highlighting the pivotal role of flexible interfaces. These interfaces not only address electrical compatibility issues between diverse devices and systems but also maximize the value of energy storage through rapid response and precise control, serving as a "coordinator" between renewable energy sources and the main grid. In the future, as technology advances—such as through improved conversion efficiency and reduced costs—flexible interfaces are expected to be adopted in more scenarios, providing robust technical support for the large-scale and high-proportion grid integration of renewable energy.

2.4. Flexible interconnection core layer

In the flexible interconnection structure of the new energy grid-connected system, the core layer of flexible interconnection is the key part that connects the aggregation section and the grid side, and it plays a role in overall regulation and efficient connection.

After processing the centralized power delivered by the aggregation link, the power electronic device converts the form of electrical energy, transforming DC power into AC or vice versa, to adapt to different grid connection scenarios. Dynamic power regulation output is also relatively crucial. If the power generation from new energy sources fluctuates due to natural conditions, it can quickly balance the supply and demand of electricity to avoid such fluctuations from impacting the grid. It can also adjust the output state according to changes in grid frequency and voltage. The core lies in its "flexible" regulation capability, which means it can flexibly control the flow and distribution of electricity based on actual needs, adapting to the volatility of new energy generation. Due to its strong compatibility, it can not only connect to new energy power but also work in coordination with various devices such as energy storage equipment and flexible loads, achieving the integrated utilization of multiple resources. Additionally, it has a basic fault isolation capability. If an anomaly

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is detected, it can quickly cut off the connection between the problem area and the system to protect the overall operational safety.

The flexible interconnection core layer enables seamless integration of renewable energy into the power grid through dynamic regulation, rapid response, and multi-agent coordination. It facilitates stable grid connectivity while fostering synergistic interactions between renewable sources and the grid, serving as the fundamental infrastructure for achieving "flexible interconnection".

Within the flexible interconnection architecture of renewable energy grid integration systems, the structural characteristics of converters as core components are meticulously tailored to their functional requirements and operational environments. Since the electrical energy generated from renewable sources often differs from grid specifications—such as photovoltaic systems producing direct current and wind turbines generating alternating current with frequency variations dependent on rotational speed—converters facilitate precise power conversion and regulation through the coordinated operation of power conversion modules, control and drive units, and thermal management systems. The power conversion module comprises multiple standardized submodules, while the integrated design of the control and drive unit consolidates functions such as signal acquisition, logic processing, and drive command generation into miniaturized circuitry. This enables reactive power adjustment to stabilize grid voltage or active power modulation in response to dispatch commands, thereby supporting grid frequency stability.

3. Coordinated control strategy

3.1. Principles of control strategy

The coordinated control principle of flexible interconnection technology plays a pivotal role in renewable energy grid power generation processes. By employing multidimensional 协同 control techniques, it achieves dynamic balance and efficient interaction among renewable power generation, energy storage systems, loads, and the grid. This addresses the inherent randomness and volatility of renewable energy output, thereby ensuring the secure and stable operation of the power system while enhancing energy utilization efficiency [7]. The following is an overview of the relevant fig 1 illustrating the control strategy principles.

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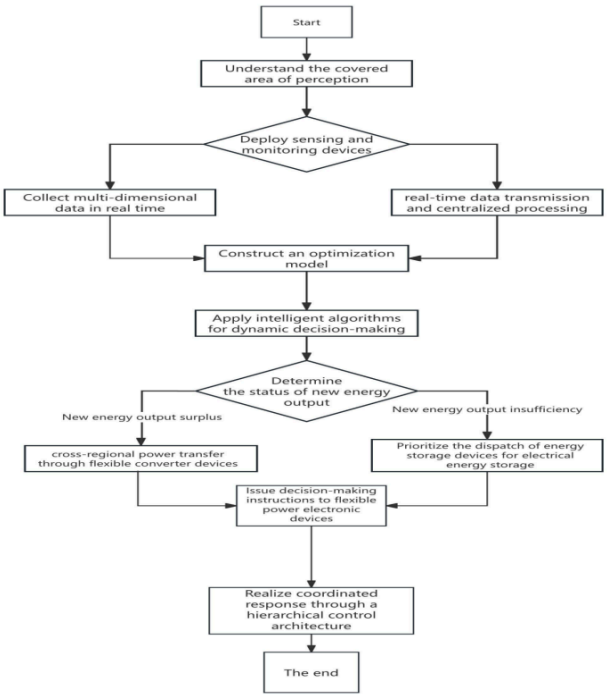


Figure 1. Schematic flowchart of the control strategy

The profound significance of this control strategy lies in promoting the transformation of the power system from being "centered on traditional power sources" to "dominated by new energy sources".It not only resolves the volatility issue of new energy through technical means, but also lays the foundation for the development of the energy internet by establishing a multi-agent collaborative operation mode.In the future, with the integrated application of technologies such as digital twins and edge computing, the flexible interconnection control strategy will demonstrate greater potential in enhancing the system's self-healing capacity and optimizing the efficiency of energy allocation.

3.2. Local coordinated control of flexible interconnection devices

Conventional flexible interconnection devices predominantly adopt a two-terminal structure utilizing back-to-back voltage source converters. Under normal operating conditions, these devices employ grid-following control strategies—specifically constant active power, constant reactive power, and constant DC bus voltage control—to achieve flexible interconnection between regional distribution networks through precise output current regulation [8]. However, such grid-following converters exhibit current-source characteristics, passively tracking grid frequency without the capability to independently form a microgrid, thus presenting limitations in ensuring stable operation of critical loads. Consequently, research on control methodologies for multi-terminal flexible interconnection devices with grid-forming capabilities has been conducted. Taking an n-terminal (n>2) system with multiple VSCs as an example, each VSC's AC side connects to multiple feeders, while the DC side is linked to the DC bus via a DC capacitor. Under this configuration, the local coordinated control strategy is designed as follows: For any designated VSC_1 among the n converters, grid-forming control based on DC bus voltage synchronization is implemented. During grid-connected operation, this control adjusts the active power output of VSC_1 in response to DC bus voltage variations, thereby maintaining power balance within the device. In islanded operation,

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the phase and amplitude of VSC_1's modulation voltage are derived from DC bus voltage changes, establishing a stable frequency and voltage to form a local microgrid and ensure a reliable power supply to critical loads. While VSC_1 operates in grid-connected mode, the remaining VSC_i (i=2,…,n) utilize constant active and reactive power control to track power reference commands, facilitating flexible interconnection between distribution networks. ,n)When VSC_1 transitions to islanded operation and the DC bus voltage drops below a predefined threshold, the VSC connected to the feeder with the maximum power supply margin switches to constant DC bus voltage control to stabilize the DC link voltage (Table 1).

Table 1. Control methods for multi-terminal flexible interconnection devices

Operation mode	Control object	Control strategy
VSC1 grid-connected operation	Select VSC1	Synchronous grid-forming control of DC bus voltage
Other VSC operation	VSC2—VSCn	Constant active power/constant reactive power control
VSC1 off-grid operation	Select VSC1	Establish local microgrid frequency and voltage stability
Emergency recovery of DC voltage	Maximum power supply margin VSC	Rapidly stabilize DC bus voltage

In low-voltage flexible interconnection systems, local coordinated control employs centralized or decentralized interconnection strategies to achieve load complementarity. The DC bus voltage reflects active power balance, and maintaining its stability is critical for power coordination control. Typically, one unit in the system operates in grid-connected constant DC voltage mode, while the remaining units operate in grid-connected constant power control mode. During emergency faults, the units switch to islanded mode. If the DC output voltage of a unit in grid-connected constant power control mode continuously falls below the threshold, it will automatically switch to grid-connected constant DC voltage mode to enhance system stability and power response.

From a holistic perspective, localized coordinated control of flexible interconnection devices based on new energy grid integration structures is of paramount importance. On one hand, well-designed control strategies can fully leverage the advantages of flexible interconnection devices, enhance the distribution network's capability to address challenges posed by distributed energy integration, and ensure grid stability. On the other hand, continuous optimization and refinement of localized coordinated control strategies contribute to efficient allocation of power resources, facilitate the integration of renewable energy, and promote energy transition and sustainable development. With ongoing advancements in power electronics, control technologies, and information technology, future research on localized coordinated control of flexible interconnection devices will deepen, promising more intelligent, efficient, and reliable power system operation.

3.3. Coordinated smoothing control of new energy and energy storage systems

3.3.1. Power control strategy

The main objective of power control strategies is to ensure that the charging and discharging power of energy storage systems meet the demands of the power grid. Common strategies include maximum power point tracking control and constant power control [9]. Maximum power point tracking control enables the energy storage system to track the maximum power point of the battery

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during charging, thereby enhancing charging efficiency; during discharging, it outputs the maximum power based on the grid's requirements. In photovoltaic power generation systems, when energy storage systems adopt maximum power point tracking control, they can efficiently store and release electrical energy even when light conditions change. Constant power control involves charging and discharging the energy storage system at a constant power. This control method is simple and easy to implement, making it suitable for scenarios with fixed power demands. During low grid load periods, it charges at a fixed power, and discharges at a fixed power during peak periods.

3.3.2. Energy management strategy

Energy management strategies focus on the energy status of energy storage systems, ensuring that the state of charge (SOC) of the energy storage system remains within a reasonable range to maintain the long-term stable operation of the energy storage system. In the context of multi-region grid interconnection, this strategy can be expanded to "cross-energy storage cluster SOC coordinated balancing". When the local energy storage SOC is too high due to a sudden increase in wind power in a certain region, the excess electricity can be transferred through flexible DC links to regions with insufficient photovoltaic output and low energy storage SOC, achieving an overall balance of SOC in multiple nodes and avoiding overloading or idling of energy storage in a single region. To a certain extent, it can ensure the consistency of SOC among individual battery cells in the energy storage system, avoiding overcharging or overdischarging of individual batteries and extending battery life. Additionally, based on predictive energy management strategies, by forecasting the output of new energy generation and load demand, the charging and discharging plans of the energy storage system can be planned in advance, improving the utilization efficiency of the energy storage system. Based on weather forecasts and historical load data, the photovoltaic power generation and electricity load of the next day can be predicted, and the charging and discharging of the energy storage system can be reasonably arranged to better coordinate with the generation and load demands of new energy.

3.3.3. Coordinated control strategy

The coordinated control strategy enables energy storage systems to collaborate with renewable energy generation facilities, power grids, and other energy storage systems to maximize overall benefits. In integrated source-grid-load-storage systems, energy storage systems work in conjunction with renewable energy generation equipment to mitigate fluctuations in renewable power output. Simultaneously, they cooperate with the grid by participating in frequency regulation and peak shaving, while also coordinating with other energy storage systems to achieve optimal resource allocation. In a regional grid comprising wind farms, photovoltaic power stations, and energy storage systems, the energy storage system operates synergistically with wind and solar power generation [10]. It provides timely regulation during fluctuations in renewable energy output and responds to grid dispatch commands to participate in system adjustments, thereby ensuring the stable operation of the entire power system.

Taking the interconnected distributed energy system based on a multi-terminal ring-shaped DC distribution network as an example, State Grid Putian Electric Power Company constructed the nation’s first low-voltage five-terminal ring-type flexible DC microgrid in the northern Meizhou Island. This system centers on a ring topology formed by interconnecting the DC sides of five distribution stations, employing a closed-loop structure to establish redundant power supply paths and enhance system disturbance resistance [11]. Conventional conversion processes typically incur

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approximately 20% energy loss. By adopting the multi-terminal ring-type DC distribution network as a core hub, the system constructs redundant power supply paths through closed-loop topology and integrates clean energy sources—such as photovoltaic and wind power—along with energy storage devices to mitigate intermittent energy fluctuations. It also accommodates both AC and DC loads, enabling coupled operation of multiple energy flows. Furthermore, leveraging relevant power electronic equipment, it achieves AC/DC conversion and bidirectional energy regulation. A master-slave cooperative control architecture is implemented to manage power distribution and dynamic balancing among multiple sources and loads.

The essence of coordinated control lies in achieving deep coupling of renewable energy sources, flexible interconnection, and energy storage systems through multi-source data fusion and dynamic optimization [12]. The advanced control system at Nanxingku Green Energy e-Station integrates meteorological data and next-day forecasts to generate a 24-hour-ahead charging and discharging schedule for the energy storage system. This plan is dynamically adjusted intraday based on real-time photovoltaic output, resulting in an increase of 48.12 kWh in average daily energy discharge. This strategy not only avoids frequent charge-discharge cycles but also maximizes renewable energy utilization by combining ultra-short-term forecasting with real-time corrections. Coordinated control not only mitigates slow-varying fluctuations but also addresses rapid disturbances at the second or even sub-second level [13]. Energy storage and flexible interconnection devices can rapidly inject or absorb reactive and active power, effectively supporting voltage and frequency stability at the grid connection point and in adjacent power networks.

4. Conclusion

In the research on grid integration structures for renewable energy based on flexible interconnection, a systematic validation and discourse on coordinated control methodologies has been achieved. The study elucidates the core mechanism of dynamic synergy among renewable generation units, flexible interconnection devices, energy storage systems, and loads, while clarifying the dynamic response matching mechanism between flexible interconnection devices and energy storage systems. A dynamic power balance control strategy suitable for hybrid distributed and centralized generation scenarios is proposed, and its effectiveness in enhancing system stability and optimizing renewable energy integration efficiency has been verified. Through optimized control logic, system fluctuations can be effectively reduced, leading to more stable grid integration of renewable energy. This approach provides a new pathway for the efficient grid integration of renewable energy in practical power systems and is applicable to scenarios involving multiple types of renewable energy sources. Future research could further explore the robustness of this method under extreme weather conditions that cause abrupt changes in renewable energy output, as well as extend its application to cross-regional interconnected grids. Integrating novel energy storage technologies such as sodium-ion batteries and flywheel energy storage could further deepen the understanding of the role of coordinated control in multi-objective optimization and the trade-off between energy efficiency and cost.

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