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ENERGY ROUTING MECHANISM OF ENERGY STORAGE SYSTEM BASED ON ELECTRONIC POWER TECHNOLOGY

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Abstract:

Driven by the dual forces of global energy structure transformation and the intelligent development of power systems, the energy routing mechanism of energy storage systems has become a core technology for achieving efficient energy allocation and the consumption of renewable energy. This article focuses on the application of electronic power technology in the energy routing of energy storage systems, systematically sorting out its technical principles, functional characteristics and practical value. Research shows that the energy routing mechanism based on electronic power technology significantly enhances the flexibility and reliability of energy storage systems through multi-port power conversion, bidirectional energy flow control and intelligent energy management, providing key technical support for the construction of a new type of power system.

Keywords: *Electronic power technology; Energy storage system; Energy routing; Power electronic conversion; Energy Internet.*

1. Introduction

With the continuous growth of global energy demand and the increasing proportion of renewable energy, the traditional power system is facing challenges such as difficulties in matching supply and demand and insufficient peak shaving capacity [1]. As a core link in balancing energy supply and demand, the energy management efficiency of energy storage systems directly affects the stability and economy of the power system. The energy routing mechanism, by integrating electronic power technology, realizes dynamic interaction between the energy storage system and the power grid, distributed energy and loads, and has become a key technology for building smart grids and energy Internet [2].

Electronic power technology takes power semiconductor devices as its core and achieves flexible control and efficient conversion of electrical energy through power electronic transformation. In the energy routing of energy storage systems [3], this technology realizes the bidirectional flow of electrical energy, voltage level transformation and optimized energy distribution through devices such as multi-port converters and bidirectional DC/DC converters, providing technical support for the large-scale application of energy storage systems. This paper systematically analyzes the energy routing mechanism of energy storage systems based on electronic power technology from three dimensions: technical principles, functional characteristics, and application value.

The current hardware architectures of energy routers mainly fall into two categories. The topology architecture based on solid-state transformers (SST) proposed by North Carolina State University realizes the interconnection between a 10kV medium-voltage distribution network and a 400V low-voltage microgrid through high-frequency transformers. The modular power unit stacking design enables a single module capacity of up to 50kVA. And it is equipped with a real-time thermal management system to ensure long-term operational stability [4]; The multi-port DC bus architecture proposed in the MDPI literature adopts a 400V DC bus solution, integrating an MPPT controller, battery management unit, and three-phase inverter, achieving a comprehensive energy efficiency of 98.2%, and is suitable for high-density load scenarios such as data centers [5]. In terms of control strategy research, the SPIN system developed by the Oak Ridge National Laboratory (ORNL) in the United States uses an improved ant colony algorithm for dynamic energy routing, real-time monitoring of the supply and demand status of each node, and automatically selects the path with the lowest loss, reducing line loss by 23% to 37% [6]. In terms of application scenario research, Arellano-Prieto et al. proposed a power predictive control strategy combining a hybrid energy storage system with a bidirectional DC/DC converter to address the issue of pulse load impact on offshore platforms, which narrowed the voltage fluctuation range of the DC bus from ±15% to ±3% [7].

2. Technical Basis of Electronic Power Technology in Energy Routing of Energy Storage Systems

2.1 The Core Role of Power Electronic Conversion Technology

Power electronic conversion technology is the technical cornerstone of energy routing in energy storage systems. Its core functions include the conversion of electrical energy forms, voltage level adjustment, and bidirectional energy flow control.

The conversion of electrical energy forms is achieved through technologies such as rectification, inversion, and frequency conversion, realizing the mutual conversion between alternating current and direct current. For instance, in photovoltaic energy storage systems, inverters convert direct current into alternating current for grid connection. In the charging scenario of electric vehicles, rectifiers convert alternating current to direct current to charge the battery.

Voltage level adjustment adopts technologies such as modular multilevel converters (MMC) and solid-state transformers (SST) to achieve voltage matching between medium-voltage distribution networks and low-voltage regional networks. For instance, in the microgrid of an industrial park, SST can convert 10kV medium voltage electricity into 380V low voltage electricity to meet the power demands of different loads.

Bidirectional energy flow control achieves bidirectional energy transmission between the energy storage system and the power grid through bidirectional DC/DC converters. When there is an excess of renewable energy generation, the energy storage system charges. When the peak electricity load occurs, the energy storage system discharges to achieve "peak shaving and valley filling".

2.2 Intelligent Upgrade of Digital Control Technology

Digital control technology, by integrating sensors, communication modules and intelligent algorithms, realizes real-time monitoring and dynamic optimization of energy routing. In terms of data acquisition and communication, it supports communication protocols such as Modbus and IEC 61850 to achieve high-speed data transmission between devices for instance, energy routers can collect real-time data on photovoltaic power generation, energy storage system power and load demand, providing data support for energy dispatching. In terms of intelligent decision-making algorithms, dynamic optimization of energy routing is achieved based on algorithms such as Model Predictive Control (MPC) and fuzzy control. For instance, in a multi-energy complementary scenario, the algorithm can formulate the optimal energy allocation strategy based on photovoltaic power generation prediction, load demand, and electricity price signals. In terms of fault diagnosis and self-healing, the integrated fault detection module is used to monitor the real-time operating status of the equipment. When a fault is detected, the energy router can automatically switch to the backup path to ensure the continuous operation of the system.

2.3 Structural Innovation of Multi-port Energy Routers

The multi-port energy router integrates AC ports, DC ports and energy storage interfaces to achieve unified access and management of multi-energy systems. In terms of port function design, AC ports are used to connect the mains power to the load, DC ports are used to connect photovoltaic, wind power and energy storage systems, and energy storage interfaces are used to connect batteries, supercapacitors and other devices. For example, in the photovoltaic storage direct current flexible system, The DC port can directly supply power to loads such as LED lighting and DC air conditioners, effectively reducing power conversion losses. In terms of topological structure optimization, cascaded and matrix topological structures are adopted to enhance the flexibility and reliability of energy routing. For instance, the cascaded topology achieves high-voltage DC output by series-connecting multiple H-bridge modules, while the matrix topology enables free connection between ports through a switch matrix to adapt to complex energy scenarios.

3. Functional Characteristics of Energy Routing Mechanism for Energy Storage

Systems Based on Electronic Power Technology

3.1 Bidirectional Energy Flow and Dynamic Balance

The energy routing mechanism, by means of bidirectional DC/DC converters and multi-port converters, achieves bidirectional energy flow between the energy storage system and the power grid as well as distributed energy. Specifically, in the charging mode, when there is an excess of renewable energy generation, the energy router will store the excess electricity in the energy storage system, such as during the peak period of photovoltaic power generation in the daytime. The energy router will prioritize storing electrical energy in the lithium battery to avoid the phenomenon of light abandonment. In the discharge mode, when facing peak electricity consumption or grid failures, the energy router will release the electrical energy from the energy storage system to the grid or supply it to critical loads. For instance, during the peak electricity consumption period at night, the energy router will invoke the electrical energy from the energy storage system to alleviate the peak shaving pressure on the grid. In addition, the energy router can also maintain the energy balance of the system by dynamically adjusting the direction and rate of energy flow by real-time monitoring of the power consumption of the energy storage system, the load of the power grid, and the power generation of renewable energy.

3.2 Multi-energy Complementarity and Collaborative Optimization

The energy routing mechanism supports the coordinated operation of multiple energy systems such as photovoltaic, wind power, hydropower and energy storage, and achieves the optimal configuration through energy management algorithms. Specifically, it is reflected in energy priority management. It formulates energy usage priorities based on energy costs, carbon emissions and reliability indicators. For example, in industrial parks, photovoltaic power generation is given priority, followed by energy storage systems. Finally, purchase electricity from the power grid; In terms of load following control, it can dynamically adjust energy output according to changes in load demand. For instance, in electric vehicle charging stations, the power supply ratios of photovoltaic, energy storage and the power grid can be adjusted in real time based on fluctuations in charging demand. In the autonomous operation of microgrids, autonomous operation is achieved in off-grid microgrids by coordinating distributed energy and energy storage systems. For instance, in remote areas, photovoltaic, diesel generators and energy storage systems are integrated to ensure the continuity of power supply.

3.3 Intelligent Management and Adaptive Regulation

The energy routing mechanism, by integrating artificial intelligence technology, has achieved intelligent and adaptive energy management. In terms of prediction and optimization, it predicts the power generation of renewable energy, load demand and electricity price signals based on historical data and machine learning algorithms, and formulates forward-looking energy scheduling strategies, such as predicting the power generation of photovoltaic power through LSTM neural networks. Adjust the charging and discharging plan of the energy storage system in advance; In terms of adaptive regulation, control parameters are adjusted in real time according to the system's operating status to enhance the robustness of energy routing. For instance, when the grid frequency fluctuates, the output power of the energy storage system is automatically adjusted to participate in grid frequency regulation. On the human-computer interaction interface, the system operation data, energy flow paths and dispatching strategies are displayed through the visualization platform. It supports users to customize energy management rules. For example, users can set the charging time of the energy storage system through the mobile phone APP to optimize the household electricity cost.

4. Application Value of Energy Routing Mechanism in Energy Storage Systems Based on Electronic Power Technology

The energy routing mechanism of energy storage systems based on electronic power technology has significant application value. In terms of enhancing the consumption capacity of renewable energy, it significantly improves the consumption rate by dynamically balancing the power generation and consumption demands of renewable energy. For instance, in major photovoltaic provinces such as Gansu and Qinghai, the real-time dispatching of energy storage systems by energy routers has reduced the curtailment rate from 15% to below 5%. In major power-consuming provinces such as Jiangsu and Zhejiang, the participation of energy storage systems in peak shaving has alleviated the power supply pressure during peak hours on the power grid. In off-grid areas such as Sansha City, Hainan Province, the integration of photovoltaic, diesel generators and energy storage systems has enabled the stable operation of microgrids throughout the year. In terms of enhancing the resilience and reliability of the power grid, the energy routing mechanism, through the integration of distributed energy and the coordination of energy storage systems, has improved the grid's disaster resistance capacity and power supply reliability. For instance, during the 2024 Zhengzhou torrential rain disaster, it automatically switched to the energy storage system for power supply, ensuring the continuous operation of key loads. In rural power grids, the voltage qualification rate has been raised from 92% to 98% through reactive power compensation and voltage regulation. In the event of a power outage across the entire network, diesel generators can be started through the energy storage system to achieve black start of the power grid. In promoting the construction of the energy Internet and the new power system, as a core device of the energy Internet, the energy routing mechanism has facilitated the interconnection and intelligent upgrade of the energy system. For instance, in pilot areas such as Xiongan New Area, multiple energy sources have been integrated to build a multi-energy complementary smart energy system. In cities such as Shanghai and Beijing, participate in the demand response market to guide users to adjust their electricity consumption behavior and reduce the peak-valley difference of the power grid. In the Guangdong carbon trading market, record relevant data to provide a basis for carbon quota trading.

5. Challenges and Prospects

At present, as the energy routing mechanism of energy storage systems is constantly evolving and developing, it is confronted with both technical challenges that need to be overcome urgently and promising future prospects.

In terms of technical challenges, the reliability of power semiconductor devices is a major problem. At present, the lifespan performance of IGBT, SiC and other devices in harsh environments such as high temperature and high humidity is still not satisfactory, which directly affects the stable operation and long-term use of energy routers. The absence of a standardized system also restricts its development. The interface standards, communication protocols and testing norms of energy routers have not yet been unified. Devices produced by different manufacturers are difficult to achieve seamless connection and collaborative work, which greatly limits its large-scale application. In addition, cost control is also a key issue. The cost of high-end power semiconductor devices and digital control modules accounts for a relatively high proportion, which leads to the overall cost of energy routers remaining high. It is necessary to continuously iterate technologies to reduce manufacturing costs and enhance market competitiveness.

However, the future is also full of infinite possibilities. Technological integration and innovation will become an important trend. With the rapid development of 5G, Internet of Things and blockchain technologies, energy routers will be able to achieve more efficient device interconnection and data sharing, enhancing the intelligent level of energy management. In terms of application scenario expansion, energy routers will be deeply integrated with transportation, construction and industrial fields, and closely combined with electric vehicles, intelligent buildings and industrial Internet, promoting the energy system to move towards comprehensive intelligence. Meanwhile, policy support will also be continuously strengthened. It is expected that during the "14th Five-Year Plan" period, the state will introduce more incentive policies to promote the research and development and demonstration application of energy routers from aspects such as financial support and tax preferences, creating a favorable policy environment for their development and helping them play a greater role in the energy field.

6. Conclusion

The energy routing mechanism for energy storage systems, based on electronic power technology, integrates power electronics conversion, digital control, and multi-port routing technologies to achieve efficient energy allocation and deep integration of renewable energy. This mechanism has significant value in enhancing grid resilience, promoting the development of the Energy Internet, and contributing to the goal of carbon neutrality. In the future, with technological advancements and policy support, the energy routing mechanism will become a core supporting technology for new power systems, providing a key solution for the global energy transition.

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