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Review of Research on Energy Storage Applications of Integrated Energy System

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Abstract

Integrated energy systems (IES) have emerged as a crucial solution for addressing the dual challenges of energy sustainability and environmental protection in modern society. Conventional energy systems exhibit critical limitations including low efficiency, significant carbon emissions, geographical imbalance in resource distribution, and dependence on non-renewable sources. To overcome these constraints, modern IES implementations employ coordinated operation strategies combining combined cooling, heating and power (CCHP) generation and advanced storage systems. However, the current economic viability of physical energy storage solutions remains constrained. This study proposes a virtual energy storage system (VESS) framework that integrates demand-side management with renewable energy utilization. The findings provide a theoretical foundation and practical references for optimizing multi-energy complementarity in next-generation smart energy networks.

Keywords

Integrated energy system; energy storage technology; combined cooling, heating and power; virtual energy storage system.

1. INTRODUCTION

Energy is regarded as the cornerstone of human survival and development. It is considered the lifeblood of the national economy. In recent years, an increased proportion of renewable energy has been observed in power generation. In particular, intermittent energy sources, such as wind and solar power, have been widely employed. The stability of the energy system is being challenged to a greater extent [1]. New approaches have been provided by the introduction of integrated energy storage systems. Integrated energy storage is capable of balancing fluctuations between electricity demand and supply. Moreover, multiple forms of energy, including electricity, heat, and cold, can be effectively integrated. Efficient scheduling and utilization of energy can be achieved, and the flexibility and resilience of the energy system are enhanced [2].

Integrated energy storage is further regarded as playing an important role in promoting energy transition, reducing carbon emissions, and enhancing energy security [3]. The application of energy storage technologies is observed to significantly increase the penetration of renewable energy, reduce reliance on conventional energy sources, and promote the development of a green, low-carbon economy. Meanwhile, as energy storage technologies are continuously advanced and their costs are gradually reduced, their application scenarios are

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being increasingly broadened. Tremendous potential is demonstrated in fields ranging from power systems to buildings and transportation [4].

Due to the spatiotemporal uncertainty of demand-side load energy, the improvement of energy utilization efficiency and the rational allocation of energy resources are regarded as particularly important. To address this issue, energy storage devices in the storage system are used to collect surplus energy during specific periods and to release it during peak demand periods for user consumption [5]. The energy storage subsystem is considered to play a vital role in the IES. It is employed to assist the system in effectively utilizing renewable energy and low-cost electricity, and to facilitate the transfer of loads across different time periods. Economic benefits are enhanced and stable operation is ensured. However, the high cost and long payback period of current storage devices remain the main obstacles to their widespread adoption [6]. Moreover, large-scale energy storage technology is still immature, and further research is required to achieve the goal of economic operation of the energy system.

2. DEVELOPMENT AND APPLICATION OF IES

An IES is a system in which the processes of energy generation, transmission and distribution, conversion, storage, consumption, and trading are organically coordinated and optimized during planning, construction, and operation. Through this optimization process, a high-efficiency integration of energy production, supply, and consumption is achieved [7]. In a given region, advanced physical information technology and innovative management models are employed to integrate various energy sources, including coal, oil, natural gas, electricity, and heat. Coordinated planning, coordinated management, complementary coordination, and optimized operation among various energy subsystems are thereby established.

2.1. Development status of IES

The core objective of IES is to enhance overall efficiency through multi-energy complementarity. Lund et al. [8] studied an integrated model of regional energy markets, emphasizing the role of distributed energy and storage systems in IES. Kuosa et al. [9] verified the advantages of multi-energy complementarity in improving system stability by comparing performances of traditional networks and ring networks. Cheli et al. [10] analyzed the steady-state characteristics of distributed renewable energy injection in natural gas networks and proposed strategies to optimize renewable energy integration. Alazemi et al. [11] discussed the market-oriented operation mode of hydrogen energy supply station, which provided a reference for policy formulation.

China is a major consumer of energy. In recent years, with the diversification of its economy, the energy strategy has been continuously optimized. A low-carbon, energy-saving, efficient, and safe development policy has been implemented. Meanwhile, the transformation from traditional energy systems to modern IES has been steadily promoted. Pan et al. [12] gave a comprehensive introduction to the equipment mathematical model and operation optimization model of IES. Zhang et al. [13] proposed a dynamic scheduling model of electric-gas-thermal multi-energy coupling based on deep reinforcement learning. Peng et al. [14] combined Topsis multi-objective decision-making method to build a low-carbon economic scheduling model considering demand response, which significantly reduced the peak-valley difference and operation cost.

2.2. Modelling and application of IES

IES surpasses individual systems by achieving multi-energy complementarity. They are no longer confined to a single energy supply. The storage advantages of heat and gas are utilized to realize complementary substitution among heat, electricity, and gas. As a result, the interactivity and flexibility of the power system are enhanced. Li et al. [15] proposed the concept of "source-network-charge-storage" heterogeneous energy flow complex energy supply system, and conducted in-depth research on the dynamic response characteristics and cooperative regulation of the system. Hua et al. [16] studied and applied an integrated energy control system based on the concept of multi-energy complementarity, and discussed the control strategies and effects of IES in practical applications.

3. APPLICATION MODE OF ENERGY STORAGE SYSTEMS

3.1. Practical energy storage

Photovoltaic and wind power generation are being vigorously developed to reduce carbon emissions [17]. This trend is regarded as inevitable in the evolution of integrated energy systems. A rational configuration of energy storage is expected to effectively reduce the curtailment of wind and photovoltaic power. It is considered a key factor in reducing renewable energy waste and enhancing the energy efficiency of IES [18]. In recent years, rapid developments in renewable energy technologies—especially in wind power and photovoltaics have been observed. Multiple low carbon energy supply strategies have been provided. However, low energy efficiency and limited economic benefits have been caused by the uncertainty of renewable energy and the independent operation of energy networks [19]. To balance energy consumption with renewable energy generation and to increase system flexibility, traditional methods have been employed, such as the addition of hot water tanks or batteries.

Energy storage systems are applied on the generation side to effectively prevent the surplus electricity produced by renewable energy sources from being wasted through solar and wind curtailment. Energy waste is reduced, the dispatchability of renewable energy is improved, and the impact on the grid is mitigated. In order to balance the intermittency of renewable energy generation, energy storage systems are used to enhance the grid's capacity to accommodate renewable generation and to reduce the adverse effects of renewable energy uncertainty on grid operation. Battery energy storage, due to its unique performance characteristics, has been regarded as one of the priority development directions [20]. Battery storage is used to store the surplus electricity generated by renewable sources such as solar and wind, and the stored electricity is released for user consumption when the energy supply is insufficient.

Thermal energy storage technology is based on thermal medium materials to store industrial waste heat, natural gas waste heat, solar heat and geothermal heat, and release it when needed. It is committed to solving the imbalance between supply and demand caused by the uncertainty in time and space of demand-side heat use, which greatly improves the efficiency of energy utilization. Thermal energy storage currently comprises three forms: sensible heat storage, latent heat storage, and thermochemical heat storage [21]. Sensible heat storage is recognized as the simplest and most mature technology. Among these, storage devices that use water as the heat transfer medium are the most widely applied, owing to the significant advantages of water in terms of cost and availability compared with other materials.

3.2. Virtual energy storage system

Virtual energy storage system is essentially a form of demand response on the demand side of microgrids. It is regarded as a new flexible resource and has attracted considerable attention from both academia and industry in recent years [22]. The large-scale deployment of energy storage systems is still considered unfeasible in the short term. Aggregated demand response can serve a function similar to virtual energy storage, as it provides charging and discharging functionalities by intelligently managing load power and energy consumption. Virtual energy storage is implemented by aggregating controllable loads. It is used to shift or reduce electricity demand while maintaining system energy balance, thereby achieving an indirect storage effect analogous to the charging and discharging of physical energy storage systems.

Energy storage configuration in IES is used to improve the consumption rate of renewable energy and enhance system operational flexibility. The impact of renewable energy fluctuations on the grid is effectively reduced. Energy storage devices are employed to assist the energy system in utilizing renewable energy and low-cost electricity. Load transfer across different time intervals is facilitated by these devices to promote economic operation and ensure stable system performance. However, physical energy storage is associated with high investment costs, long operational cycles, and limited configuration options. Therefore, a virtual energy storage system aimed at achieving economic dispatch can be constructed by analyzing the characteristics of controllable loads on the demand side.

4. CONCLUSION

Based on an analysis of the domestic and international status and application modes of IES, this paper presents the following study. The development status of virtual energy storage technology and its application modes under different conditions are introduced. In addition, the optimization configuration problem of virtual energy storage is investigated from the perspectives of mathematical modeling and optimization algorithms. The main conclusions and outlooks are presented as follows.

1) With the intensification of policy support for renewable energy, the development of renewable energy storage devices has gradually advanced. Virtual energy storage technology is essentially based on certain operating rules and cannot be completely separated from traditional physical energy storage.

2) Virtual energy storage technology can be integrated with physical energy storage within integrated energy systems. By coupling with these systems, a dynamic model of an energy transfer thermoelectric network can be established.

5. DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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