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Research on Coordinated Control Strategy of Integrated Photovoltaic-Storage-Charging Systems for Grid Carbon Reduction

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Abstract. This paper focuses on an integrated photovoltaic storage and charging station for grid carbon reduction. It outlines the "source-storage-load" coordination characteristics of the system, including the synergy among photovoltaic generation, battery energy storage, and electric vehicle charging facilities, as well as its integration with multi-energy systems, and systematically reviews the carbon reduction mechanisms, including PV replacing thermal power, energy storage for peak shaving and valley filling, and V2G reverse power supply. Uncertainty handling methods (e.g., forecasting techniques, robust optimization, and rolling optimization) and coordinated scheduling strategies (e.g., multi-time-scale optimization and multi-objective optimization methods) are also examined. This study not only provides a comprehensive reference for the low-carbon planning and operation of photovoltaic-storage-charging systems in the context of new power systems but also proposes fusion strategies that combine methods addressing the same problem to achieve a more comprehensive solution, supporting the transition towards a more sustainable, low-carbon energy future.

Keywords: Integrated photovoltaic storage and charging station, Multi-energy, Carbon reduction, Optimal coordinated scheduling

1. Introduction

Driven by global efforts to combat climate change and China's "dual carbon" goals, the energy system is accelerating its transition to clean, low-carbon development. As a major source of carbon emissions, the deep decarbonization of the power sector is a critical link to achieving carbon neutrality. Installed capacity for renewable energy generation, particularly photovoltaics (PV), has grown rapidly; however, PV output's intermittency and fluctuations pose serious challenges to the safe and stable operation of the power grid. Meanwhile, the large-scale adoption of electric vehicles not only increases electricity demand but also provides the grid with flexible regulation resources. Efficiently integrating PV power generation, smoothing load fluctuations, and reducing system carbon emissions has become a core issue that the new power system urgently needs to address. The integrated photovoltaic storage and charging station (IPSCS) has emerged as a response to these challenges and has become a recent research hotspot. However, existing studies tend to focus on optimization from a single technical dimension, lacking a comprehensive overview of integrating PV-storage-charging systems with multi-energy systems, their contributions to grid carbon reduction, and methods to optimize carbon-reduction benefits. Therefore, this paper adopts a literature review approach to summarize the characteristics of integrated PV-storage-charging systems, elucidate their integration with multi-energy systems, and examine their contribution to carbon reduction and the carbon reduction benefits under different scenarios. Finally, this paper summarizes methods for handling uncertainty factors that may affect IPSCS, as well as coordinated scheduling strategies for grid carbon reduction, to facilitate better operation of PV-storage-charging systems.

2. Overview of integrated photovoltaic-storage-charging systems

IPSCS is a system that integrates a photovoltaic power station, a battery energy storage system (BESS), and a charging station (CS). This system features an integrated "source-storage-load" architecture. Ccharging behavior at electric vehicle charging stations across different locations affects the optimal integration capacity of photovoltaic and battery storage; therefore, the configuration may vary across different application scenarios [1]. Meanwhile, "the integration of multi-energy and this type of infrastructure appears" [2]. The photovoltaic battery swapping-charging-storage stations (PBSCSS) mentioned in the reference demonstrate the system's flexibility and the complementarity between the multi-energy system and battery energy storage [2] . The adaptable operational modes of the photovoltaic-storage-charging system. Upon the occurrence of a malfunction in the distribution network, the Integrated Station Microgrid (ISM) can shift to islanded operation via preventive measures and decoupling management, autonomously providing power to its internal loads [3]. Once the fault is resolved, grid-connected operation can be restored via grid-synchronization control, ensuring a continuous power supply to the internal loads.

3. Contribution of the system to carbon reduction

3.1. Three main pathways to reduce carbon emissions in the power grid

3.1.1. Photovoltaic power generation replacing fossil fuel-based power generation

Replacing traditional thermal power with photovoltaic power generation achieves zero carbon emissions during operation. At the same time, it can optimize the power grid's structure, reduce overall carbon intensity, and enhance power generation flexibility.

3.1.2. Energy storage for peak shaving and valley filling to improve grid efficiency

"Energy storage can participate in grid regulation across multiple time scales and plays an important role in improving the utilization rate of renewable energy" [4]. In addition, energy storage reduces curtailment of wind and solar power and supports higher penetration of renewable energy into the grid. In a photovoltaic-storage-charging system, it maximizes photovoltaic consumption. It supplies green electricity to electric vehicles, avoiding thermal power use during peak hours and thereby reducing carbon emissions.

3.1.3. Electric vehicle V2G (vehicle-to-grid) reverse power supply to reduce thermal power backup

V2G reverse power supply discharges during peak hours, replacing thermal power peak-load units with low efficiency and high coal consumption, thereby reducing carbon emissions per unit of electricity generated. The low-carbon demand response mechanism proposed demonstrates a proportional relationship between V2G discharge participation and carbon-reduction benefits—the higher the response level, the greater the carbon-reduction effect [5].

3.2. Tiered carbon emissions

The tiered carbon-emission strategy proposed in establishes dynamic carbon-emission factors based on time-of-use electricity pricing [6]. It stratifies carbon emissions, effectively reflecting the carbon emission situation during interactions between the integrated station and the grid at different times. Furthermore, the proposed dynamic tiered carbon cost charging model introduces penalty coefficients that apply high charges and costs to limit carbon emissions. This strategy provides valuable insights into carbon-reduction approaches in integrated stations.

3.3. Carbon reduction effects of the system under different renewable energy penetration rates

The gradually increasing penetration rate of renewable energy has exerted various impacts on the power system's operational mode, influencing the results of system capacity configuration and posing challenges to the security and reliability of the new power system. Moreover, studies have shown that the system's carbon-reduction effect varies with different levels of renewable energy penetration. The golden section search (GSO) algorithm to construct a multi-layer capacity-optimization configuration model for a wind–solar–thermal–storage system [7]. It provides optimal capacity configurations under different penetration rate constraints and performs a fitting analysis, identifying the pattern that, as system penetration increases, economic costs rise, stability decreases, while carbon-reduction benefits increase. Therefore, to achieve a favorable carbon-reduction effect in a photovoltaic-storage-charging system, it is essential to consider the renewable energy penetration rate, which underscores the necessity and importance of optimized scheduling.

4. Coordinated control strategies for grid carbon reduction

The uncertainty in photovoltaic output and electric vehicle load constitutes the main challenge in coordinated control, and uncertainty handling and coordinated dispatch optimization are the means to achieve better grid carbon reduction.

4.1. Uncertainty handling methods

4.1.1. Forecasting techniques

Both photovoltaic output and EV load can be forecast using techniques. IPSCSs are primarily equipped with distributed photovoltaic power stations, which exhibit strong spatiotemporal characteristics, robustness, and high economic efficiency. Currently, distributed photovoltaic power generation forecasting technologies mainly fall into two categories: direct forecasting based on historical power generation modeling, and indirect forecasting that estimates solar radiation intensity from meteorological data. Optimization suggestions for distributed photovoltaic power generation forecasting techniques, including data-driven approaches, historical power data, and meteorological factors [8]. It proposes strengthening distributed photovoltaic uncertainty forecasting by advancing from current point forecasting to probabilistic and interval forecasting. It further elaborates that photovoltaic forecasting can draw on similar approaches to wind power generation, offering strong insights into its future direction and application in IPSCSs.

Currently, EV load forecasting techniques are mainly divided into model-driven and data-driven categories, but still face challenges such as complex model construction and low forecasting accuracy. At present, forecasting methods based on deep learning technologies are gradually becoming a research hotspot, with methods such as long short-term memory (LSTM) and gated recurrent unit (GRU) being widely used. Large language models (LLMs) have demonstrated strong potential in forecasting due to their powerful data processing and comprehension capabilities. The principles, core architecture, and application scenarios of LLMs [9]. It considers aspects such as electricity price forecasting, highlighting the benefits of LLMs' small-sample learning and adaptive generalization in improving forecasting accuracy. It also highlights shortcomings, such as the challenge of ensuring data privacy and security, and offers promising directions for integrating LLMs into the power grid. However, due to the high spatial uncertainty of EV loads, it combines charging pile utilization rates with charging loads to build an LSTM-based forecasting model that accounts for the spatial distribution characteristics of EVs, thereby significantly improving forecasting accuracy [10]. This strategy can be implemented together with the cloud computing strategy proposed to achieve EV load forecasting [11].

4.1.2. Optimization strategies

Optimization strategies mainly include two-stage robust optimization for worst-case scenarios, rolling optimization for real-time correction, and frequency division control. Two researchers propose two-stage robust optimization methods to address worst-case scenarios [2, 12]. The two papers elaborate on the application of this method at the operational and planning levels, respectively. They perform uncertainty modelling regarding internal coupling within a singular PBSCSS station and multi-user shared energy storage in parks, utilising a "min-max" robust optimisation framework, defining uncertainty set boundaries, and adjusting conservatism via uncertainty budget parameters to guarantee system reliability under extreme conditions. If future research necessitates comprehensive robust optimisation from planning to operation, the methodologies from both papers can be integrated to ascertain optimal capacity configurations and multi-time-scale operational strategies, thus facilitating a more thorough application of the two-stage robust optimisation approach in worst-case scenario simulations. However, issues such as the over-conservatism of the two-stage robust optimization solution, difficulty in representing risk preferences, and high computational complexity mean that this method still has certain limitations. The adaptive frequency division control strategy proposed decomposes the DC voltage deviation signal into high- and low-frequency components, which are then allocated and regulated based on their respective frequency regulation capabilities [13]. This strategy can also be applied to IPSCS systems, where components such as BESS, photovoltaic inverters, and charging piles can respond to high-frequency and low-frequency fluctuations. However, attention must be paid to constraints such as the state of charge and strong randomness.

4.2. Optimal coordinated scheduling

4.2.1. Multi-time scale

Multi-time scale methods have been widely used in optimization strategies for coordinated scheduling in recent years. By performing rolling optimization of the power grid at the day-ahead, intra-day, and real-time levels, they play an important role in reducing uncertainty, improving equipment matching, enhancing economic efficiency, and ensuring reliability. It combines multi-time-scale optimization with robust optimization, adopting a three-stage rolling correction to effectively cope with PV and EV fluctuations across multiple time scales, thereby reducing uncertainty [2]. Moreover, it covers multiple energy sources and adopts model predictive control (MPC), which offers a flexible rolling mechanism and strong adaptability to forecast errors [4]. In recent years, breakthroughs in multi-time-scale methods have also been made. The Parametric Autotuning Multi-Time Scale Optimization (PAMSO) algorithm, proposed to address the issue of large-scale models, introduces a parameter self-tuning method. By decomposing the problem into high-level and low-level decisions and introducing tunable parameters to bridge the gap between them, it achieves an efficient solution to extremely large-scale problems [14]. The multi-agent, multi-time-scale aggregated regulation method proposed in Ref [15]. combines day-ahead and intra-day scheduling, employing multiple algorithms to achieve spatio-temporal coordination of user-side resources, significantly reducing scheduling costs. When applied to IPSCS, multi-time scale methods can reduce the impact of forecast errors, balance economy and reliability, and support multi-level coordinated operation.

4.2.2. Multi-objective optimization methods

In coordinated scheduling, common optimization objectives include multiple aspects: economic (minimizing operating costs), technical (minimizing load peak-to-valley differences, maximizing renewable energy integration), low-carbon (minimizing carbon emissions), and user satisfaction (minimizing charging costs, etc.). In practical engineering, multiple objectives often conflict, making multi-objective optimization essential. It constructs a multi-objective model, uses the Analytic Hierarchy Process (AHP) to calculate the weight coefficients for each objective, and employs the Ant Lion Optimizer (ALO) to solve the problem, thereby improving upon the traditional weighted-sum method for multi-objective optimization [16]. In contrast, it applies the Pareto front method to the bi-level multi-objective optimal scheduling of microgrid clusters with electric vehicles, solving it using the intelligent algorithms NSGA-II and Particle Swarm Optimization (PSO) [17]. This method can address non-convex Pareto front issues that the weighted-sum method cannot handle, offering a broader scope and eliminating the need for subjective weight setting, thereby demonstrating greater advancement in solving complex coordinated scheduling problems in energy systems.

5. Conclusion

This paper provides an overview of the composition and characteristics of the integrated photovoltaic-storage-charging system, which has become a research hotspot in recent years—including the key roles of PV, energy storage, and charging facilities as well as their "source-storage-load" coordination mechanism—and the potential for its integration with multi-energy systems. It also focuses on the system's contribution to grid carbon reduction, achieving emission reductions through pathways such as PV replacing thermal power, energy storage for peak shaving and valley filling, and V2G reverse power supply. Moreover, it introduces novel carbon-reduction methods and the differences in carbon-reduction benefits across various scenarios. Finally, the paper summarizes and compares commonly used and emerging coordinated scheduling methods (e.g., robust optimization, MPC, multi-time-scale rolling optimization) at this stage, while also proposing the possibility of integrating several methods for combined application. The research topic of this paper addresses a gap in discussions on the advantages of IPSCS for carbon reduction. It provides a comprehensive summary of methods for handling uncertainties in PV output and EV charging loads, as well as optimization strategies for coordinated scheduling. However, this paper lacks a discussion of the balance between carbon-reduction benefits and economic viability. This balance is precisely the key bottleneck to the practical promotion and application of the system. Future research can make breakthroughs in the following aspects: 1) Conduct empirical comparisons across multiple scenarios and penetration rates to quantify the carbon reduction potential under different configurations; 2) Develop an integrated planning-operation collaborative carbon reduction framework that jointly optimizes capacity configuration and operational scheduling; 3) Promote the linkage between V2G commercial mechanisms and the carbon trading market to establish a sustainable low-carbon operation model.

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