

Key Technologies and Review of Hosting Capacity Assessment for Distributed Photovoltaic Integration into Distribution Network

Lijing Han

*School of Automation, Central South University, Changsha, China
2936492762@qq.com*

Abstract: In response to the challenges posed by large-scale distributed photovoltaic (PV) integration to the safe operation of Distribution Network (DN), this research systematically explores pathways for enhancing hosting capacity. First, based on the dynamic characteristics of PV output and the theory of DN security margins, it reveals the key mechanisms behind issues such as voltage limit violations and reverse power flow induced by high PV penetration. Second, by comparing traditional hosting capacity assessment methods in terms of computational accuracy, scenario adaptability, and intelligence levels, the study identifies the limitations of existing methods in balancing multidimensional constraints and spatiotemporal dynamics. Then, considering source-network-load-storage resources, including topology enhancement, energy storage configuration, and demand-side response, the research explores the mechanisms for improving DN hosting capacity from the perspectives of coordinated planning and optimized operation. Finally, recommendations are proposed by integrating technical and policy aspects to provide theoretical support for enhancing hosting capacity and facilitating low-carbon transitions in DN with high PV penetration.

Keywords: Distributed photovoltaic, Distribution network (DN), Hosting capacity, Assessment, Planning, Operation

1. Introduction

With the accelerating global energy transition, the energy structure is shifting from traditional fossil fuels to clean energy sources. Driven by the "dual carbon" goals, China's energy sector is undergoing unprecedented transformations. The National Energy Administration emphasizes that the DN, as a crucial component of the power system, plays a vital role in ensuring electricity supply, supporting economic and social development, and improving public welfare. However, the rapid development of DRE poses severe challenges to the hosting capacity of DN. On the one hand, the stochastic, intermittent, and fluctuating nature of renewable energy increases the difficulty of operational control. On the other hand, large-scale DRE integration imposes higher requirements on voltage regulation, power flow control, and network stability. Consequently, assessing and enhancing the hosting capacity of DN has become a critical research topic.

The hosting capacity of DN is closely related to the secure operation of the network and the type of energy integration. The safe and stable operation of DN is key to ensuring reliable electricity supply. Yilida highlights that enhancing efficiency while maintaining secure and reliable power supply is an

urgent issue for DN [1]. It defines key fault sets, evaluation metrics, and solution methods, offering a new perspective on improving distribution system security. As the penetration of renewable energy continues to increase, power balance and voltage stability in DN face significant pressure. Additionally, the issue of renewable energy curtailment has become more prominent, with local curtailment of wind and solar power frequently occurring. Liu and Zhang points out that the root cause of wind and solar curtailment lies in the mismatch between the speed of new energy generation capacity expansion and local consumption capabilities [2]. Enhancing the hosting capacity of DN can not only improve the accommodation capacity for renewable energy but also effectively alleviate energy curtailment issues, thereby promoting a clean and low-carbon energy transition. Furthermore, improving hosting capacity is crucial for ensuring the safe and stable operation of the power system, enhancing power supply reliability, and reducing operational costs.

In recent years, scholars worldwide have conducted extensive research on assessing and improving the hosting capacity of DN. Men and Zhao proposes an improved Simulated Annealing-Particle Swarm Optimization (SA-PSO) algorithm, which enhances the convergence speed and optimization capability of the assessment model compared to other algorithms. Under the same constraint limits, the optimized SA-PSO algorithm achieves higher distributed PV hosting capacity and lower system network losses. However, merely establishing an assessment model is insufficient [3].Gong and Xu presents a comprehensive hosting capacity coefficient model by quantitatively evaluating the operational state of DN. By incorporating renewable energy integration capacity, the study proposes a comprehensive hosting capacity model and an optimized energy storage configuration method for enhancing DN hosting capacity [4]. This study complements the findings of Men and Zhao by adopting a holistic network perspective [3]. Considering the impact of large-scale distributed generation integration, the novel introduces a source-load uncertainty model that accounts for instability in energy sources and demand [5]. Meanwhile, Zhang discusses a novel interval assessment approach for evaluating hosting capacity in DN with emerging loads [6]. However, most existing studies focus on single technologies or localized assessments, lacking a systematic and holistic perspective.

Addressing the challenges brought by large-scale distributed PV (DPV) integration, this research first systematically analyzes the impact of increasing renewable energy penetration on DN security margins based on the theoretical framework of hosting capacity and the dynamic characteristics of PV output. Second, it systematically reviews the technical characteristics and applicable scenarios of existing hosting capacity assessment methods. Through a multidimensional efficiency comparison—including computational accuracy, scenario adaptability, and intelligence level—the study reveals the limitations of traditional methods. Furthermore, a "planning-operation-control" coordinated optimization framework is proposed, constructing hosting capacity enhancement strategies from three perspectives: topology reinforcement, dynamic power flow control, and demand-side response. Finally, an innovative spatiotemporal correlation feature mining algorithm is introduced, along with an intelligent hosting capacity assessment model for DN based on deep reinforcement learning(DRL). Additionally, policy mechanisms and technological standard updates are proposed as recommendations for future development.

2. Hosting capacity of DN and challenges after PV integration

2.1. Hosting capacity of DN

Hosting capacity is a broad concept whose specific meaning varies by application domain. Generally, it refers to the maximum load or capacity a system, structure, or entity can sustain under specific conditions, such as safety, stability, economy, and environment. It reflects the system's resource, capability, or capacity limits. The hosting capacity of a DN refers to its maximum ability to safely

and stably accommodate and absorb various distributed generation (DG) sources and loads under normal operating conditions. It embodies the comprehensive performance of the DN in terms of structure, equipment, and control strategies. The evolution of its maximum capacity has progressed through the early exploration phase, the technology-driven and assessment research phase, the policy guidance and goal-setting phase, and the digital and intelligent transformation phase, ultimately entering a future-oriented, multi-domain collaborative development phase, forming a comprehensive research framework for DN hosting capacity.

DN hosting capacity encompasses four aspects: electrical capacity, thermal capacity, control capacity, and communication capacity. Factors affecting these aspects include network structure, equipment performance, DG characteristics, load characteristics, and control strategies, all of which influence the overall performance of the DN. The integration of renewable energy into DN has become a mainstream development trend. Traditional energy sources such as wind and solar are gradually evolving, but this transition triggers chain reactions, such as the obsolescence and inadequacy of traditional hosting capacity assessment methods and the limitations of conventional capacity enhancement approaches. Therefore, developing novel assessment and enhancement methods for DN hosting capacity is crucial for networks integrating large-scale distributed generation.

2.2. Impact of large-scale PV integration on DN hosting capacity

With the introduction of the "dual carbon" targets and the nationwide implementation of county-wide PV development policies [7], DPV, a representative form of DG, is being widely integrated into DN. DPV harnesses solar energy for electricity generation without producing greenhouse gas emissions or other pollutants, replacing traditional fossil fuels and significantly reducing carbon emissions, which helps mitigate climate change. Additionally, DPV integration can reduce network losses, improve energy accessibility, drive the energy transition, and create employment opportunities, alleviating social employment pressures. According to the National Energy Administration's Management Measures for DPV Development and Construction" DPV enable local power generation and consumption, reducing long-distance transmission losses and lowering electricity costs. DPV offers significant advantages in environmental, economic, technical, and social aspects, making it a crucial component of future energy systems.

Despite its numerous benefits, DPV integration also introduces new challenges. The large-scale integration of DPV significantly alters power flow distribution in DN, increasing the risk of voltage limit violations and causing voltage imbalance and quality deterioration [8]. Due to DPV's random, fluctuating, and uncertain output characteristics, as well as its flexible participation in demand response, the operational characteristics of the grid undergo significant changes. These issues, including reverse power flow and voltage limit violations, ultimately impact the hosting capacity of the DN. As DPV capacity increases, DN hosting capacity approaches saturation, limiting further integration. Addressing and mitigating the challenges posed by DPV integration can significantly enhance its benefits, enabling DPV to play a greater role in the DN sector.

3. Capacity assessment methods

3.1. Traditional capacity assessment methods

Numerous studies have been conducted on the assessment methods for the hosting capacity of DN. For example, Liang Haiping et al. [9] proposed a DG capacity assessment model that aims to maximize the DG integration capacity while considering constraints such as voltage deviation, voltage fluctuation, short-circuit current, and relay protection. Koirala et al. [10] introduced a heuristic approach, while HAN et al. [11] and Dong Yu et al. [12] developed linearization techniques to address nonlinear problems in power systems by transforming nonlinear objective functions and

constraints into a linear format, thereby optimizing the mathematical analytical method. Liu Keyan et al. [13] leveraged interdisciplinary knowledge and applied a multi-population genetic algorithm to evaluate hosting capacity.

Although these assessment methods have been refined over time, they still suffer from issues such as low algorithm accuracy and slow convergence speed. Furthermore, existing methods do not comprehensively consider the primary constraints limiting DPVgrid integration, namely, node voltage violations and reverse overloading of distribution transformers [3]. Many traditional assessment methods only take a single constraint—such as voltage or relay protection—into account when building DPV hosting capacity assessment models. This approach fails to address the challenges posed by large-scale PV integration. Additionally, traditional assessment algorithms are often complex and difficult to apply to large-scale problems, limiting their applicability. Therefore, developing a new, more generalizable hosting capacity assessment model that considers multiple constraints is of critical importance.

3.2. Novel capacity assessment methods

In recent years, several studies have explored innovative capacity assessment methods. Men and Zhao not only developed a novel distributed photovoltaic (DPV) hosting capacity assessment model for medium-voltage distribution networks (DNs) but also proposed an improved simulated annealing-particle swarm optimization (SA-PSO) algorithm. This model's objective function incorporates the impact of DPV integration on network losses [3], while its constraints focus on node voltage violations and reverse overloading of distribution transformers, effectively addressing the limitations of traditional assessment methods that consider only single constraints such as voltage or relay protection. Additionally, the novel established a hierarchical DPV hosting capacity assessment system that provides a comprehensive evaluation of DPV hosting capacity in DN [14]. This study applied a combination weighting method that integrates the analytic hierarchy process (AHP) and the entropy weight method to quantify evaluation indicators, generating an overall capacity evaluation score. Unlike purely theoretical approaches, this method involves precise DN modeling and simulations, considering multiple operational constraints and their interdependencies, leading to a more practical evaluation approach based on overall system indicators. Lv addressed the issue of uncertainty in source-load resources, which was not effectively considered in previous studies. It proposed a DPV hosting capacity assessment method that accounts for the stochastic nature of source-load resources [5]. By constructing and extracting operation scenarios, this study built a DPV hosting capacity evaluation model with multiple constraints. Furthermore, it introduced a comprehensive assessment framework to quantitatively analyze the operational status of DN under different DPV integration scenarios, providing valuable data support for new DN operation strategies and renewable energy investment planning. Zhang presented an interval evaluation method for assessing the maximum hosting capacity of DN for new types of loads [6]. This method fully considers the uncertainty of electric vehicle (EV) charging loads, the power fluctuation of thermostatically controlled loads (TCLs), and the uncertainty in the reliable dispatch of flexible resources. It effectively calculates the maximum hosting capacity of DN for emerging loads. This study fills a research gap in the interval assessment of maximum hosting capacity setpoints and addresses the issue of overly optimistic evaluations that arise from ignoring uncertainty factors in conventional deterministic assessments.

4. Methods for enhancing the hosting capacity of DN with DPV integration

As discussed in the previous sections, large-scale DPV integration into DN can lead to issues such as reduced power supply capacity and insufficient regulation capability. The following sections will

explore methods to enhance the hosting capacity of DN from both planning and operational perspectives.

4.1. Planning aspects

From a planning perspective, Chen studied the impact of PV grid integration locations on voltage levels and applied the TOPSIS method to optimize PV capacity selection [15]. This research focused on PV site selection and capacity allocation as a means to improve DN hosting capacity. Li and Sun developed a multi-objective optimization model to evaluate the performance of PV hybrid systems in terms of productivity and power supply reliability, aiming to achieve optimal system configuration [16]. Building on previous research, the novel introduced the concept of the generalized short-circuit ratio to assess the operational security of DN [17]. It examined PV site selection and capacity allocation strategies that take DN hosting capacity into account, improving network performance by considering node voltage correlation margins. This approach helps determine the power distance between each node's power capacity and its maximum allowable limit. Consequently, a two-level planning method was proposed for PV site selection and capacity allocation, evaluating hosting capacity in terms of power quality and safety to derive optimal solutions for enhancing DN hosting capacity.

Kong, Wang and Han [18] addressed the volatility of wind and PV energy in wind-PV-storage-hydrogen systems and the dynamic response characteristics of hydrogen storage. It proposed an online power regulation method for wind-PV-storage-hydrogen coupling systems based on model predictive control (MPC) with weight adjustment. This method can be applied to DN planning by forecasting scenarios for renewable energy integration, selecting appropriate control strategies, planning multi-energy microgrids with PV-storage-hydrogen integration, and designing dynamically reconfigurable networks. These measures ensure long-term balance between renewable energy integration and load distribution, thereby enhancing hosting capacity.

Existing studies often lack quantitative analyses of critical indicators such as power flow distribution and power quality. A comprehensive assessment of DN operation and energy storage status should be incorporated when evaluating hosting capacity. Regarding capacity enhancement techniques, energy storage systems (ESS) play a crucial role due to their efficient energy storage and rapid charge-discharge characteristics. Many studies have optimized ESS configurations to improve DN's ability to accommodate renewable energy. The novel [18] proposed strategies such as reconfigurable switches and mobile energy storage to enhance PV hosting capacity. There are applied robust optimization methods to ESS configuration in DN, improving hosting capacity under extreme conditions, though the planning results tended to be conservative with relatively poor economic efficiency [19-20]. Gong synthesized existing ESS optimization schemes and developed a novel DN hosting capacity model [4]. Based on this model, a comprehensive ESS optimization method was proposed to enhance overall hosting capacity, aiming to maximize integrated hosting capacity while minimizing economic costs. This approach promotes the healthy operation of DN and the efficient utilization of wind and solar energy, ultimately improving comprehensive hosting capacity.

4.2. Operational aspects

In recent years, the large-scale integration of DG and the sharp increase in electricity demand have made optimizing the operation of DN a critical issue. To enhance hosting capacity, it is often necessary to calculate network losses during operation to determine the optimal DN reconfiguration. Liu integrated traditional genetic algorithms, neural networks, simulated annealing, and branch exchange methods, incorporating the impact of DG. It proposed an operational strategy that simultaneously optimizes DN reconfiguration and reactive power management by developing

voltage-optimal and load-optimal mathematical models, ultimately enhancing hosting capacity [21]. Hu and Dong identified a key issue in existing intelligent data-driven operation strategies based on graph convolutional networks (GCNs), where improper penalty coefficient settings could lead to frequent voltage limit violations in DN operation [22]. To address this, a two-level optimization strategy based on the state-response framework was proposed. This approach bypasses the constraints of penalty coefficients by transmitting real-time voltage states to a response layer after power flow calculations. This method effectively mitigates voltage violations and ensures optimal operational conditions, thereby improving hosting capacity. From an operational perspective, Huang proposed a two-level stochastic optimization strategy for DPV integration, solving optimization problems from both upper and lower operational levels [23]. This study considered boundary conditions such as PV penetration rate and load growth rate to determine the impact on configuration results, ultimately enhancing hosting capacity from an optimal operational standpoint.

Li highlights that it explored the coordinated optimization of source-network-load-storage under new power system frameworks and developed a digital twin model [24]. By constructing an optimization model and solving it with an improved firefly algorithm, this study leveraged digital twin technology to simulate an integrated source-network-load-storage operation system for DN. The model pre-simulates high-penetration renewable energy integration scenarios, using a novel simulation platform to identify optimal DN operation strategies, ultimately improving hosting capacity.

5. Future prospects

5.1. Technological advancements

In the future, DN will develop towards greater intelligence, flexibility, and digitalization. The deep integration of various cutting-edge technologies will be a key approach to enhancing their hosting capacity.

In terms of intelligence, artificial intelligence (AI) and big data technologies will be deeply embedded in the operation and management of DN. According to Wang, real-time regulation and analysis of massive datasets will enable precise forecasting and flexible control of new types of loads, such as distributed energy resources (DERs) and EVs [25]. For instance, big data-based load forecasting models can predict peak loads in advance, thereby optimizing DN operation strategies, efficiently allocating power resources, and improving supply reliability. Additionally, AI algorithms can autonomously detect and quickly locate grid faults, reducing outage durations and enhancing power supply service quality.

Flexible technologies will enhance the adaptability and resilience of DN. Shi highlights that the application of flexible DC transmission and energy storage technologies will allow DN to better accommodate the intermittency and uncertainty of DERs [26]. ESS can store surplus electricity when DER generation exceeds demand and release it during shortages, playing a critical role in peak shaving and valley filling to improve the network's DER hosting capacity. Furthermore, flexible interconnection technologies enable power exchange between different DN regions, optimizing resource allocation and improving overall operational efficiency.

Digitalization will provide strong support for real-time monitoring and efficient control of DN. As Shu and Tang discussed the Energy Internet technology enables interconnectivity among various devices in the DN, forming a vast intelligent sensing network [27]. By equipping devices with sensors, real-time monitoring of operational status and power quality can be achieved, facilitating comprehensive visibility into DN conditions. Additionally, the combination of cloud computing and edge computing will provide robust computational capabilities, supporting complex data processing and analytical tasks, thereby enabling refined DN management.

In the future, the integration of more advanced technologies with DN will further enhance their hosting capacity, contributing to the energy transition and sustainable industry development.

5.2. Policy support

In terms of policy planning and coordination, governments can introduce more favorable policies related to DN development. For example, the “Guiding Opinions on High-Quality Development of DN under the New Situation” explicitly emphasize the significant role of DN in ensuring power supply and improving public well-being, as well as the necessity of enhancing their hosting capacity.

From a financial and economic perspective, the Guiding Opinions on High-Quality Development of DN under the New Situation issued by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) propose that the government should support eligible DN projects through central investment guidance and local government special bonds. Furthermore, financial institutions are encouraged to enhance their financial services to support DRE, charging infrastructure, and new energy storage projects. These policies not only provide financial support for DN upgrades but also foster an enabling environment for technological innovation and industry development.

In summary, future government initiatives can introduce additional policies to encourage advancements in DN hosting capacity. With strong policy support, the evaluation and enhancement of hosting capacity will be effectively promoted, laying a solid foundation for energy transition and the modernization of power sector.

6. Conclusion

To address issues arising from large-scale DPV integration, such as voltage limit violations, reverse power flow, and reduced security margins, this research integrates DPV dynamic characteristics analysis with hosting capacity theory to reveal the evolution mechanisms of operational risks in high-penetration scenarios. A collaborative “planning-operation-control” optimization framework for DN incorporating DPV integration is proposed.

Through an in-depth analysis of intelligent assessment models enhanced by DRL, this study explores the advantages of topology reinforcement, dynamic power flow control, and demand-side response strategies in improving DN adaptability to PV fluctuations. Furthermore, combined with policy coordination and iterative updates to technical standards, the research outlines key technologies for enhancing DN hosting capacity under high DPV penetration conditions. Future research should explore multi-resource collaborative optimization pathways for PV-storage-load systems, promote refined modeling approaches, and advance multi-energy complementary dispatch technologies. The ultimate goal is to achieve both efficient renewable energy integration and the secure and economic operation of power grids.

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