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The Analysis of Robust Optimization Methods in the Field of Virtual Power Plants

Ruize Wang[1,a,*]

[1]School of Automation, Wuhan University of Technology, Wuhan, 430070, China
a. 1635932791@qq.com
**corresponding author*

Abstract: With the global energy transition and the rapid development of renewable energy, power systems are facing unprecedented challenges. As an innovative solution integrating and coordinating distributed energy resources, the virtual power plant (VPP) has gained increasing importance in the energy market, emerging as a highly regarded field in recent years with widespread applications. In response to many popular issues within this field, this paper categorizes them into three main aspects: cooperation/competition, market transactions and bidding strategies, as well as scheduling and forecasting. It examines the applications of robust optimization methods in each of these areas. Lastly, the paper summarizes potential future research directions for robust optimization, anticipating the development of more versatile methods that can address issues in the VPP field by considering multiple factors comprehensively.

Keywords: Robust optimization, virtual power plants, energy market, market transaction, uncertainty.

1. Introduction

In recent years, the scale and diversity of distributed energy resources (DERs) integrated into distribution networks have been steadily increasing, leading to increasingly severe supply-demand imbalances[1]. Against this backdrop, the field of virtual power plants (VPPs) has become a hot topic. As a novel aggregation and management technology for distributed energy, VPPs are known for their efficiency, flexibility, and user-friendly characteristics[2]. A VPP can integrate flexible resources such as small gas turbines, wind turbines (WT), photovoltaics (PV), energy storage, and controllable loads into a unified system. It engages in power purchasing and sales transactions in external markets, while internally coordinating resources, significantly optimizing resource dispatch and reducing the uncertainties affecting the grid. However, the renewable energy sources within a VPP, such as wind and photovoltaic power, are characterized by high randomness and uncertainty, which complicates optimal resource integration. Therefore, a key focus of future discussions will be how to properly account for the uncertainty of renewable energy output and adjust the bidding and operational strategies of VPPs. This paper, based on existing literature and research data, focuses on a classical optimization method — robust optimization. It provides a general overview of how this method is applied across various fields within VPPs, and offers a summary of its advantages and disadvantages. The conclusions of this study aim to inspire future scholars to develop more comprehensive robust optimization models, facilitating the rational allocation of societal resources, promoting the

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integration of renewable energy into the grid, and enabling VPPs to make sound economic decisions to optimize their economic benefits.

2. Introduction to robust optimization methods

In the 1970s, Soyster introduced the robust optimization method for linear programming. By the 1990s, robust optimization began to evolve into a formal theoretical framework, with scholars such as Bertsimas and Nemirovski laying the mathematical foundation for it. Their work primarily focused on linear programming, quadratic programming, and semidefinite programming problems, all of which dealt with varying forms of data uncertainty. In 2004, Bertsimas and Sim proposed a new robust optimization method for linear programming, which significantly advanced the development of the field[3]. The goal of robust optimization theory is to find a “robust” solution in uncertain environments, one that performs well even under worst-case scenarios when faced with parameter or data uncertainty. Robust optimization is widely applied in fields such as engineering design and energy management. Unlike traditional methods that often require probabilistic distributions of uncertain parameters, robust optimization enables decision-making without needing this information, offering advantages such as fast computation and strong risk mitigation[4]. The method’s significant advantages in handling uncertainty make it particularly well-suited for the VPP sector. VPPs depend on multiple distributed energy sources, and the complexity of the market environment adds layers of uncertainty. For this reason, robust optimization methods have been widely applied within the VPP domain, enabling more reliable and efficient energy management amidst fluctuating conditions.

3. Applications of robust optimization methods

3.1. Collaboration/competition among multiple virtual power plants

To reduce risks or enhance profits, many VPP operators collaborate to coordinate and manage various dispatchable resources, such as wind power, photovoltaics, and electric vehicles. Scholars like Yan Liang and Qingqing Zhou integrated distributed wind power, energy storage, and electric vehicles into a multi-agent system and proposed a multi-stage robust optimization method based on a risk control model for VPP alliances and market bidding strategies[5]. This method considers unfavorable conditions caused by wind power fluctuations and suggests adding interconnections between VPPs. A comparative analysis of the ratio between the minimum expected return and average return, with and without considering VPP alliances, showed improved expected returns.

Regarding the issue of competitive bidding games among multiple VPPs, Songqi Jia and other scholars proposed a bidding strategy based on non-cooperative game theory and robust optimization for multiple VPPs participating in the day-ahead electricity market. This strategy helps determine the comprehensive clearing scheme for each VPP in the day-ahead marke, demonstrating practical significance[6]. Numerical analysis also showed that VPPs participating in the bidding process can enhance their individual benefit levels through alliances. VPPs primarily based on renewable energy can form alliances to monopolize the market and achieve higher returns, while VPPs using traditional generation units as their main power source can leverage their stable output to attempt alliances with VPPs containing renewable energy units, thereby enhancing their competitiveness.

3.2. Trading and bidding strategies

In multi electricity markets and for specific products, robust optimization methods have their unique advantages. Scholar Zhouyi Zhou and colleagues, focusing on the multi-tier electricity-carbon coupling market, proposed a multi-tier market trading process. To mitigate the impact of uncertainties in renewable energy output within the VPP during the two stages of trading, they successfully

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established a two-stage adaptive robust optimization model for VPPs. Compared to traditional robust optimization methods, this approach considers the adjustments in the second-stage decision-making process, allowing VPPs to focus on seeking higher profits in the first stage. Case studies demonstrated a 5.82% increase in expected revenue compared to traditional methods, reducing the conservatism of VPP operations and improving overall profitability.[7] In the context of the "dual carbon" goals, given the need to incorporate flexible ramping products (FPR) into operational strategies and the fact that the effectiveness of VPP strategies is affected by multiple uncertainties, such as renewable energy output and electricity market prices, Yuhong Fei and several scholars proposed a two-stage distributionally robust optimization (DRO) strategy that incorporates FPR[7][8]. This strategy provides valuable insights for VPP operations by balancing economic dispatch and robust risk management under uncertain conditions.

Addressing the uncertainty in WT and PV output, along with price fluctuations, Haocheng Wang and his colleagues developed a VPP operational strategy that combines renewable energy and gas turbine units based on robust optimization principles[9]. Additionally, to address spot market price uncertainty, a study applied robust optimization methods to handle the uncertainties of spot prices in the electricity market, establishing a robust equivalence model and verifying its effectiveness through simulation examples[10].

3.3. Scheduling and forecasting

The power generation of renewable energy sources is highly uncertain. In recent years, with the increasing adoption of electric vehicles (EVs) in power systems, scholars such as Yang Lv and Ruihan Diao have utilized robust interval optimization methods to effectively manage uncertainties from both the supply and demand sides. Their approach balances system robustness and economic efficiency, providing a strategy for VPPs to address the cost management issues associated with large-scale EV charging and discharging[11]. Given the widespread use of DERs in recent years, appropriately integrating these resources into the grid has become a key challenge. Linyuan Li and Changxin Yan explored the voltage-reactive power robust optimization issue in grids with high penetration of distributed renewable energy[12]. They developed a robust optimization model for voltage and reactive power in renewable energy-based grids, offering a feasible solution to the reactive power optimization problem under high DER integration. Yuankun Liu and Yujun He combined robust optimization with risk management by refining the uncertainty set in robust models. They applied this method to the optimal dispatch problem of VPPs integrating distributed generation and energy storage, ultimately achieving a balance between the economic efficiency and safety of VPP operations[13].

4. Discussion

In conclusion, the robust optimization approach is widely applied in VPPs and demonstrates its strong versatility. However, robust optimization models also have certain limitations. For instance, they tend to be overly conservative, which can limit optimization potential and make it difficult to fully maximize profits. To address these issues, methods such as distributed robust optimization or adaptive robust optimization can be explored. Traditional robust models may also suffer from inherent drawbacks, such as difficulties in defining appropriate uncertainty sets. When the uncertainty set is too large, decision-making strategies can become overly conservative; conversely, when the set is too small, they may become excessively aggressive. To address these challenges, in addition to using distributed and adaptive robust optimization, constructing multi-scale uncertainty sets or dynamic uncertainty sets can help better define uncertainties, leading to more satisfactory outcomes.

Regarding specific problems in the VPP domain, for competition and cooperation among multiple market participants, increasing the number of decision-making entities could lead to broader and more adaptable solutions. For issues related to market trading and operational strategies, a more comprehensive consideration of market prices and uncertainties associated with loads should be integrated into the decision-making process. Beyond the uncertainties of renewable energy and electricity market prices, the internal load uncertainties of VPPs should also be factored in. As for scheduling and forecasting, more comprehensive methods can be applied to handle complex power flow equations, while joint optimization involving multiple VPPs can be considered for scheduling to achieve broader applicability. This will enhance the robustness and practicality of robust optimization models in addressing a wider range of challenges in the VPP field.

5. Conclusion

This paper introduces the active application of robust optimization methods in the field of VPPs, tracing the development of this theoretical framework from its inception in the 1970s to its widespread use today. The analysis focuses on three key areas within the VPP domain: cooperation and competition, market trading and bidding strategies, as well as scheduling and forecasting. The study reveals that robust optimization still faces challenges, such as being overly conservative and accurately defining uncertainty sets. To address these issues, several improvement suggestions have been proposed. The paper primarily concentrates on the application of robust optimization in power market transactions, acknowledging that the current scope of analysis is not yet comprehensive. In future research, the focus will be expanded to offer a more systematic and holistic analysis of this method, exploring its applications in areas such as distributed energy scheduling, vehicle-to-grid (V2G) interaction, and energy storage system optimization.

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