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From Aggregation to Market: A Systemic Paradigm for Virtual Power Plants to Unlock Demand-Side Flexibility

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The proliferation of large-scale distributed energy resources (DERs) at the demand side offers considerable regulation potential for enhancing the operational flexibility of power systems. However, the inherent dispersion, heterogeneity, and uncertainty of DERs pose significant challenges to their effective integration and utilization. Virtual Power Plants (VPPs) with advanced communication and computation technologies have emerged as a promising solution to aggregate and manage these geographically scattered resources. Yet existing research lacks a standardized paradigm to guide VPP operation in terms of resource aggregation, market participation, and operational dispatch. To bridge this gap, this paper proposes a systemic "aggregation evaluation-market bidding-command decomposition" paradigm for VPPs to unlock and harness demand-side flexibility. The paradigm begins with a comprehensive evaluation of the aggregate regulation capacity of DERs, followed by the development of an optimal bidding strategy for multi-market participation, and concludes with an efficient internal dispatch mechanism that decomposes market clearing instructions into executable setpoints for individual DERs. The proposed coordinated and scalable paradigm can facilitate the efficient integration of large-scale self-interest DERs and offer practical insights for the construction and operation of high-performance VPPs.

INTRODUCTION

Recently, the rapid deployment of renewable energy sources (RESSs) for deep decarbonization has profoundly challenged the power system's stability and operational safety, creating an urgent demand for flexible regulation resources.[1] As the flexibility of traditional regulatory resources, primarily thermal power plants, becomes increasingly constrained, State Grid Corporation of China has explicitly stated its goal to leverage demand-side distributed energy resources (DERs) such as photovoltaics (PVs), battery energy storage (BES), electric vehicles (EVs), and flexible loads to provide more than 5% of the system's peak shaving capacity by 2025.[2] However, DERs are often geographically dispersed and exhibit diverse response characteristics, which complicates their centralized management and dispatch.[3] There is a significant gap between the growing demand for flexibility and its practical utilization, due to the lack of effective aggregation mechanisms. Flexibility requirements extend beyond mere capacity, emphasizing the critical need for rapid response capabilities, a certain duration of sustainability, and high reliability to participate in diverse electricity markets.[4] Consequently, this top-down push for measurable, reliable, and scalable load-side flexibility provides a strong practical impetus for the research into virtual power plants (VPPs), which have gained prominence as an efficient solution for integrating DERs through advanced communication and control architectures to operate as a unified dispatchable entity.[3-6] Unlike the traditional power plants with predictable and controllable outputs, the strong randomness and time-varying response characteristics of heterogeneous DERs introduce significant uncertainty, making it challenging to assess VPP's available capacity accurately.[7,8] Besides, since aggregate DERs usually have different owners, conflicts of interest are inevitable during the scheduling process of VPPs. Under such conditions, it is difficult to guarantee fairness and economic efficiency in profit distribution, which reduces participants' engagement enthusiasm and operational performance of VPPs. These challenges highlight a critical research gap: the absence of a standardized systemic paradigm for VPP operation that integrates technical aggregation, market participation, and internal dispatch. Consequently, this paper proposes an "aggregation evaluation-market bidding-command decomposition" paradigm for VPPs to unlock and exploit demand-side flexibility, facilitating efficient integration of large-scale DERs into power systems, as shown in Figure 1.

SYSTEMIC PARADIGM FOR VIRTUAL POWER PLANTS

Evaluation of Aggregate Regulation Capacity from DERs

Accurate evaluation of the aggregate regulation capacity of a VPP derived from a diverse portfolio of heterogeneous DERs forms the foundation for its bidding and scheduling activities. This capability enables the VPP to make credible commitments in various electricity markets and provide guaranteed services to the power system. Importantly, this evaluation moves beyond a simple summation of the nameplate capacities of individual DERs. Instead, it constitutes a sophisticated process that quantifies the dynamically controllable potential of aggregated DERs, enabling them to function as a unified and reliable entity. Without precise assessment, the VPP's market bids would resemble a gamble that risks both the underutilization of available resources and, more severely, the failure to deliver on promised services to the power system. Such failures could result in financial penalties and erode market trust. However, achieving accurate evaluation is fraught with challenges, primarily stemming from the inherent uncertainty and heterogeneity of DERs' natural and social behaviors, including solar irradiance, individual driving patterns, human usage preferences, and industrial production habits. Addressing this challenge requires a holistic framework built upon several key technological pillars including robust communication infrastructure, operating baseline forecasting, and characteristic modeling. First, a robust communication infrastructure serves as the essential hardware foundation, incorporating cloud-edge-device coordination, integrated communication terminals, and a centralized VPP control platform. This enables the collection, fusion, and management of high-resolution, real-time data streams from smart meters, IoT sensors, and edge-computing devices, providing reliable and low-latency data support for subsequent decision-making and operational processes in VPP applications. Then, baseline forecasting estimates the routine energy consumption or generation of DERs using probabilistic

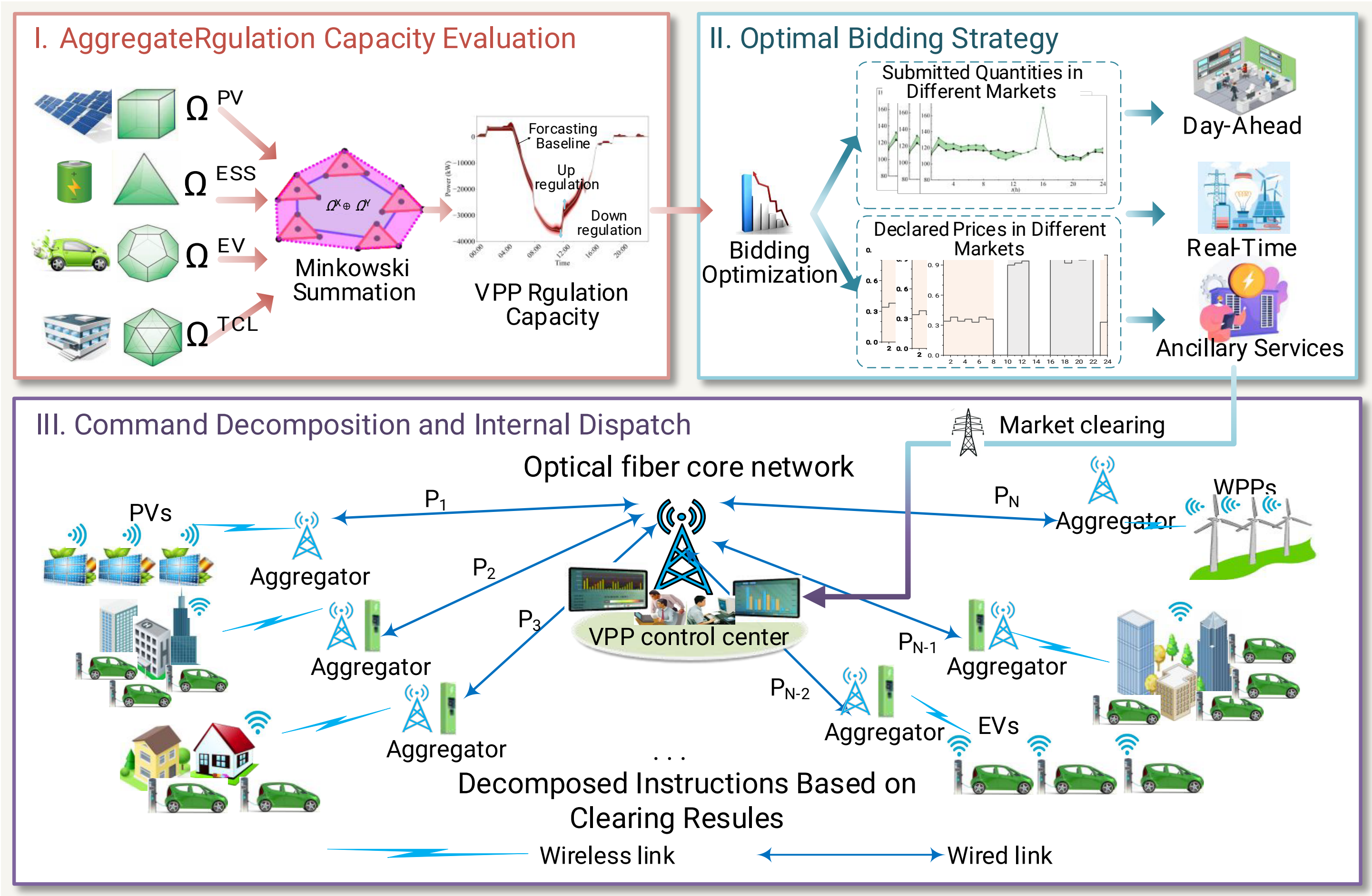

Figure 1. "Aggregation evaluation-market bidding-command decomposition" paradigm for VPPs.

forecasting or machine learning methods. Operational characteristic modeling involves developing mathematical representations of the upward/downward flexibility of each DER, capturing the key Regulation parameters such as maximum power shift, time duration, and energy state. The next step is the aggregation of these individual flexibility capabilities into a unified dispatchable capacity profile. This is typically achieved using mathematical techniques such as Minkowski summation, which combines the flexibility sets of individual DERs to compute the feasible aggregate flexibility domain of regulation power and energy around the baseline. Mathematically, the flexibility of each DER can be represented as a polyhedron in a multi-dimensional space, and the Minkowski summation effectively superimposes these polyhedra to form the combined feasible set.[8] It is also crucial to incorporate distribution network constraints, including voltage limits, thermal ratings, feeder congestion, and power flow distribution into the evaluation process, ensuring operational safety of the power system, an aspect that is often overlooked yet critical for reliable operation of VPPs.

Optimal Bidding Strategy for Multi-Market Participation

The optimal bidding strategy for a VPP, i.e., the precise quantity-price pairs in different time periods, is the cornerstone of its commercial viability. Such strategies can be deployed for participation in a single market or, more effectively, harnessed to navigate the complex interplay of multiple market opportunities. These include the day-ahead energy market, real-time balancing market, green electricity market, and various ancillary service markets, e.g., peak regulation, frequency regulation, and energy reserve. Through coordinated engagement across these venues, VPPs can maximize revenue while actively managing inherent risks. The primary challenge in designing bidding strategies lies in formulating the stochastic bidding optimization model that incorporates uncertainties from renewable generation, volatile market prices, and unpredictable behaviors of flexible loads using probabilistic forecasts and risk-constrained scenario trees. The objective function of the bidding model typically aims to maximize the expected profit, subject to constraints such as the aggregate regulation capacity of DER portfolio, market access constraints, and physical distribution network limitations.

A cost-effective multi-market bidding strategy for VPPs should incorporate explicit mechanisms for market risk aversion, often through coordinated participation across sequential electricity markets. Such strategies adopt risk measures such as value-at-risk, conditional value-at-risk, and entropic value-at-risk to balance the expected profit with exposure to price volatility and performance penalties. These strategies typically begin by allocating the available regulation capacity to the high-value ancillary service markets which provide premium availability payments. Subsequently, the remaining capacity is strategically bid into energy markets, including day-ahead and real-time markets, using robust/distributionally robust optimization techniques. By incorporating risk-aversion criteria, VPPs can avoid the undue risks and maintain reliability in meeting bidding commitments. Ultimately, the risk-aware bidding strategies enable VPPs to exploit temporal and spatial arbitrage opportunities across multiple products and market stages, thereby unlocking the multi-timescale regulation capabilities of DERs while strengthening their role as schedulable assets for the power system

Command Decomposition and Internal Dispatch

Following the optimal multi-market bidding strategy, VPPs will receive the cleared market results including the awarded energy or ancillary service quantities in each scheduling time period from the market operator. Upon obtaining these cleared outcomes, the critical subsequent procedure for VPPs becomes the internal dispatch and decomposition of these assigned instructions to its aggregated DERs for physical execution. The challenge then shifts from revenue maximization to executable feasibility, i.e., translating these high-level market commitments into specific and technically feasible setpoints for the diverse portfolio of DERs. This process requires the internal dispatch optimization models and control strategies that disaggregate the aggregate awarded power/energy trajectory while rigorously respecting the real-time operational constraints of each DER, including the state-of-charge of BES, min/max power limits of distributed PVs, flexible load comfort boundaries as well as the physical limits of the hosting distribution network to avoid congestion and voltage violations.

Concretely, the internal decomposition and dispatch processes rely on efficient coordination and control methodologies such as distributed optimization, hierarchical control, machine learning-based decision-making, and fault-tolerant control mechanisms. Operating on a much shorter timescale and with higher-fidelity data than the day-ahead bidding process, it incorporates real-time updates on renewable generation, flexible load availability, and network conditions. The objective is to compute the cost-optimal combination of DER setpoints that collectively meet the VPP's market commitments, minimizing imbalance costs and avoiding performance penalties. To address the challenges of scalability and coordination among massive heterogeneous DERs, game-theoretic approaches and mean-field control theory are increasingly employed. Game-theoretic mechanisms can facilitate coordination among strategically interacting heterogeneous DERs by modeling their decision-making processes and guiding them toward the VPP-level optimal equilibria. Meanwhile, mean-field control can efficiently manage large populations of similar DERs by analyzing their statistical distribution rather than individual behaviors, significantly reducing computational complexity. Moreover, the fair profit distribution mechanism is also necessary to allocate the market profits based on the marginal contribution of each DER, ensuring the long-term sustainability and participation willingness. Consequently, through the application of these advanced decomposition and control techniques with the benefit allocation mechanism, the VPP ensures the credibility of its bids and maintains its reputation as a reliable market participant.

CONCLUSION

This paper presents a systemic paradigm of "aggregation evaluation-market bidding-command decomposition" for VPPs to unlock the latent flexibility from diverse DERs. In this paradigm, aggregation evaluation serves as the essential foundation, enabling accurate quantification of the regulation capacity of aggregated resources. We also point out that market bidding acts as the critical pathway for economic viability, allowing VPPs to leverage aggregated flexibility across multiple electricity markets for maximizing profitability. Besides, command decomposition stands as the operational core that determines performance efficacy of VPPs, ensuring that market clearing instructions are accurately disaggregated into executable setpoints for individual DERs. Together, these three key stages form a closed-loop architecture that enhances the integration of large-scale self-interested DERs with different ownerships, offerings both theoretical and practical guidance for the deployment of high-performance VPPs.

REFERENCES

1. Chen X. (2024). Green and low-carbon energy-use. *Innov. Energy* **1**:100003. DOI:10.59717/j.xinn-energy.2025.100003
2. Kai J., Nian L., Kun W., et al. (2025). Spatiotemporal assessment of renewable adequacy during diverse extreme weather events in China. *Nat. Commun.* **16**:5198. DOI:10.1038/s41467-025-60264-9
3. Abdolahzadeh A., Hassannia A., Mousavizadeh F., et al. (2025). Multi-objective stochastic model optimal operation of smart microgrids coalition with penetration renewable energy resources with demand responses. *Sci. Rep.* **15**:22443. DOI:10.1038/s41598-025-04958-6
4. Han M., Zheng K., Hu H., et al. (2025). Long-duration energy-storage technologies: A stabilizer for new power systems. *Innov. Energy* **2**:100077. DOI:10.59717/j.xinn-energy.2025.100077
5. Kuan Z., Ya X., Nian L., et al. (2025). Customized mean field game method of virtual power plant for real-time peak regulation. *IEEE Trans. Sustain. Energy* **16**:1453–1466. DOI:10.1109/TSTE.2025.3533929
6. Chen X., Wang J., Guo L., et al. (2020). A distributed control method for air conditioning load grouping based on Lyapunov optimization. *CN Patent*. No. ZL201710431606.4.
7. Morstyn T., Farrell N., Darby S.J., et al. (2018). Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. *Nat. Energy* **3**:94–101. DOI:10.1038/s41560-017-0075-y
8. Meng S., Ze X., Ci G., et al. (2025). Distribution Dynamic Operating Security Space Characterization for Aggregation and Congestion Capacity Evaluation of Virtual Power Plant. *IEEE Trans. Smart Grid.* **16**:3904–3918. DOI:10.1109/TSG.2025.3570448

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DECLARATION OF INTERESTS

Jizhen Liu is the Editor-in-Chief of Energy Use and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group