



Toward Large-Scale DER Aggregation: Competitive Aggregation, Operation Support, and ISO-Aggregator-Utility Coordination

Final Project Report

M-46

Power Systems Engineering Research Center
*Empowering Minds to Engineer
the Future Electric Energy System*



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Executive Summary

This report summarizes research outcomes from project M46 in the PSERC market stem. Led by Professor Lang Tong (Lead PI, Cornell University), Professor Subhonmesh Bose (University of Illinois Urbana-Champaign), and Professor Meng Wu (Arizona State University), this project focused on the theoretical and practical challenges of aggregating distributed energy resources in distribution systems for wholesale market participation under the general framework of FERC Order 2222.

Aggregating distributed energy resources in distribution systems for wholesale market participation involves complex system and market interactions. This project pursued a bottom-up approach to address key technological barriers at each market interface: (i) the interfaces between a distributed energy resource (DER) aggregator (DERA) and its customers where generation, storage, and flexible demand resources are aggregated, (ii) the interface between DERAs and a wholesale market operator (ISO/RTO) where DERAs participate in wholesale energy, reserve and regulation markets, (iii) the interface between DERAs and a distribution utility where the utility provides planning and operation support for delivering the aggregated DER from end customers to the wholesale markets, and (iv) the interface between a distribution utility and an ISO where the ISO maximizes net benefits of market participants and mitigates risk subject to system constraints.

This project developed aggregation models, optimal aggregation strategies for DERAs, and coordination mechanisms for aggregators, distribution utilities, and wholesale market operators at multiple market interfaces, as well as aggregators' wholesale market participation approaches. Among the most significant outcomes of the project are an auction mechanism that defines DERAs' passways to the transmission system without interfering with the normal operations of the distribution utility, a competitive aggregation strategy that ensures customers of DERA with higher consumer surplus than that under the default regulated retail tariff, and a virtual storage participation model in the wholesale market achieving the same market efficiency as if distributed energy resources participating directly in the wholesale market.

In particular, this project investigates large-scale, competitive, and profit-maximizing aggregation technologies that benefit DERA customers more than the prevailing net energy metering-based retail tariffs. The project examines the impacts of DER aggregation uncertainties at all interfaces and develops risk mitigation strategies. The project investigates distribution system planning and operation solutions supporting DER aggregation, DERA bidding strategies in the wholesale markets, and ISO market clearing and settlement solutions. The project delivers technical assessments and comparative studies on the feasibility and cost/benefit analysis.

This project contributed to the graduate education of 6 students, giving them opportunities to interact with industry and pursue fundamental yet practically impactful research. Student research resulted in several significant awards, including the 2025 PES Outstanding Doctoral Dissertation Award, the 2023 PESGM Prize Conference Award, and several PESGM Best Paper Session selections.

Part I: Wholesale Market Participation of DERAs: DSO-DERA-ISO Coordination

The landmark ruling of the Federal Energy Regulatory Commission (FERC) Order 2222 aims to remove barriers to the direct participation of distributed energy resource aggregators (DERAs) in the wholesale market operated by ISOs/RTOs. Since distributed energy resources (DERs) originate in a distribution network, aggregated DERs must pass through the distribution grid managed by a distribution system operator (DSO) that can be the distribution utility or an independent entity. A coordination mechanism among the DSO, ISO, and DERAs is necessary to ensure system reliability and open access to all DERAs. FERC Order 2222 recognizes the significance of DSO-DERA-ISO coordination while leaving the specifics of the coordination design to the regulators, market operators, and stakeholders.

This work develops a novel DSO-DERA-ISO coordination mechanism aimed at achieving efficient and reliable multi-DERA aggregations with minimal deviations from existing DSO and ISO/RTO interaction models. Specifically, we propose a forward auction run by the DSO that allows DERAs to acquire network access limits—the right to inject or withdraw any amount of power within those limits over which the auction outcomes stand. These limits are auctioned off in a way that all power transactions from DERAs within these limits will satisfy distribution system operation constraints. Thus, DERA’s wholesale market interaction with the ISO in real-time can be agnostic to these operational constraints, and ISOs can dispatch DERs without direct visibility into the distribution network. The DERA-ISO interaction can include models such as demand response, virtual storage, etc., and any way they choose to operate the DERs will not violate distribution network security as long as they remain within the network access limits they acquire from the DSO-operated auction. Consequently, our design removes the need for DSO’s interventions in ISO’s real-time dispatch and DERAs’ aggregation actions under normal system operating conditions.

We consider two network access allocation mechanisms. First, a robust optimization-based market clearing formulation for network access is proposed, which guarantees satisfaction of network constraints when DERAs aggregate within their acquired access limits, thus removing the need for DSO to participate in real-time DERA-ISO interactions. DERAs do not even need knowledge of the underlying physical network when its aggregation strategy respects said limits. The robust access allocation can be conservative in that it assumes the worst-case aggregation and network operating conditions. Second, we develop a risk-based stochastic allocation mechanism that allows DSO to share the common network resources subject to an acceptable risk constraint on network security violations. For both the robust and stochastic access limit auctions, we provide theoretical analyses and empirical studies to characterize and quantify access allocation properties, including the nonnegative surpluses for DSO, the benefits of participating in the access limit auction for DERAs, the behavior of access allocation prices, and extensive numerical comparisons.

Part II: Wholesale Market Participation of DERAs: Competitive DER Aggregation

We address open problems in the direct participation of distributed energy resource aggregators (DERAs) in the wholesale electricity market operated by regional transmission organizations and independent system operators (RTOs/ISOs), under the general framework of FERC order 2222. We focus on the aggregation strategy of a profit-seeking DERA, whose industrial, commercial, and residential customers have competing service providers, such as their incumbent regulated utilities.

The central theme of this work is to develop profitable and competitive aggregation strategies to attract and retain customers. By competitive aggregation, we mean that the benefits of the DERA customers must be no less than those offered by electricity provider benchmarks. An example of such a benchmark is the incumbent utility or a community choice aggregator (CCA) adopting net energy metering (NEM) policies, offering strong incentives to prosumers with behind-the-meter (BTM) DERs. A major barrier to DERA's entry into direct wholesale market participation is the lack of an effective aggregation strategy and participation model, which would make DER aggregation a profitable venture.

The technical challenge of designing a profitable and competitive DER aggregation is twofold. First, the DERA plays a dual role in the aggregation process: an energy supplier to its customers in the retail market and a producer/demand in the wholesale market. Its aggregation must consider retail competition, distribution network access limits, and its overall revenue adequacy. To this end, a DERA needs to derive profit-maximizing bids/offers from its competitive aggregation. Second, competitive aggregation requires the DERA to offer more attractive pricing to its customers than the regulated tariff and shield them from the volatility of wholesale market prices.

In this project, we develop a DERA aggregation model that aggregates customers across multiple locations in distribution networks and incorporates security constraints on network injection and withdrawal limits. We further investigate the competitive aggregation impact on market efficiency, price stability, and long-run equilibrium. First, we propose a DER aggregation approach based on a constrained convex optimization that maximizes DERA surplus while providing higher customer surpluses than those offered by a competing aggregation model. We show that such a competitive DER aggregation, despite the aggregation involving real-time wholesale locational marginal price (LMP), has an energy cost no greater than the regulated NEM tariff. This implies that the proposed DER aggregation mechanism ensures price stability regardless of the volatility of the wholesale market LMP.

Second, we propose a virtual storage model for DERA's wholesale market participation compatible with the practical continuous storage facility participation considered by ISOs under FERC order 841. The DERA bidding curve is derived from the closed-form solution of the proposed DERA model. While the aggregation optimization explicitly involves wholesale market LMP, the virtual storage bidding curves do not require forecasting of LMP. We show that the proposed DERA wholesale market participation results in market efficiency equal to what is achievable when DERA's customers participate directly in the wholesale market.

Finally, we derive the benefit function of DERA over distribution network injection and withdrawal access limits. DERAs compete in the distribution network access auction proposed in Part I to acquire network access, and we empirically evaluate the number of surviving DERAs in

the long-run competitive equilibrium. We also present a set of numerical results, comparing the surplus distribution of the proposed competitive aggregation solution with those of various alternatives, including the regulated utility. Among significant insights gained are the higher social surplus, customer surplus, and DERA surplus achievable in the proposed competitive DERA model, when compared to other alternatives.

Part III: Coordinating Transmission and Distribution System Operations for Intensive DER Integration: A Parametric Programming Approach

Part III of this report establishes full-scale online transmission and distribution (T&D) coordination in future DER-rich markets by developing theoretical coordination frameworks, low-time-complexity algorithms, and distribution system pricing designs. To ensure real-world applicability, we strictly follow several design requirements for DER-rich T&D-coordinated markets. 1) Under extremely limited communications between T&D systems, T&D operation should be coordinated with minimal T&D communications. 2) To respect data ownership and model confidentiality, exchanging T&D system models should be avoided. 3) To enable a smooth transition from today's established ISO markets, T&D coordination should minimize the changes to ISO's existing market operations. 4) T&D-coordinated markets should guarantee optimal operation while satisfying all the operating constraints for the entire T&D systems. 5) To enable online operations, computations of large-scale T&D-coordinated markets should be fast.

The above requirements call for fast online coordination of a large-scale decentralized network optimization problem under extremely limited communications and zero model exchange, which is theoretically and computationally challenging.

To address the above technical challenges, three chapters are presented in Part III of this report.

Chapter 1 presents theoretical frameworks for T&D-coordinated market operation with guaranteed real-world applicability, leveraging parametric-programming-based multilevel system decomposition. This chapter presents a framework to coordinate ISO and DSO operations, compatible with the current wholesale market structure, without introducing additional changes to the existing wholesale market clearing procedure. In this coordination framework, DER aggregators participate in the wholesale market through coordination with the DSO, which ensures the secure operation of the distribution grid. A parametric programming approach is proposed to construct the bid-in cost function for the DSO (to be submitted to the ISO) and to run the DSO-level market-clearing procedure, which is based on offers collected from DER aggregators. The parametric-programming-based ISO-DSO coordination enables complete decoupling between the solution process of the ISO and DSO optimization sub-problems. This avoids iterative ISO-DSO communications within each wholesale market clearing interval and allows the ISO and DSO to exchange the minimal amount of public data only after each entity reaches its optimal solution. The proposed approach requires no exchange of private/confidential ISO or DSO grid model data.

Chapter 2 presents distribution system pricing designs that can efficiently and economically support T&D-coordinated economic dispatch via parametric programming. This chapter extends the T&D coordination framework in Chapter 1 by developing theoretical justifications and

thorough discussions for the T&D-coordinated pricing problem. Specifically, we prove and discuss 1) the relationship between the T&D-coordinated dispatch model and the T&D-coordinated pricing model, which together guarantee the T&D operation optimality for both the dispatch and pricing processes; and 2) the non-profit characteristics of the DSO under the proposed T&D-coordinated pricing model. One interesting finding is that, to ensure zero T&D model exchange and minimal T&D communication in the parametric programming-based T&D coordination framework, the optimal prices for aggregated DERs in the distribution system cannot be directly obtained from the dual of the DSO economic dispatch problem. Instead, a separate DSO pricing model is needed to generate accurate price signals for DSO-level resources and to coordinate with the ISO-level pricing and dispatch process.

Chapter 3 presents low-time-complexity algorithms for online T&D-coordinated market operation by developing minimum-cost flow algorithms and cutting-plane methods. In this chapter, we introduce two algorithms for addressing the ISO-DSO coordination problem, as initially presented in Chapter 1. The first algorithm focuses on solving the ISO-DSO coordination parametric programming problem without accounting for voltage constraints. The second algorithm builds on the first by dynamically incorporating voltage constraints to determine a solution that satisfies all of them. We provide mathematical proofs to demonstrate the optimality of both algorithms. Furthermore, we extend the algorithms to accommodate unbalanced three-phase systems.

Project Publications:

- [1] A. N. Madavan, N. Dahlin, S. Bose, and L. Tong, “Risk-Sensitive Security-Constrained Economic Dispatch: Pricing and Algorithm Design,” to appear in *IEEE Transactions on Power Systems*, doi: 10.1109/TPWRS.2025.3589590.
- [2] C. Chen, S. Li and L. Tong, “Multi-Interval Energy-Reserve Co-Optimization With SoC-Dependent Bids From Battery Storage,” in *IEEE Transactions on Power Systems*, vol. 40, no. 4, pp. 3008-3016, July 2025, doi: 10.1109/TPWRS.2024.3509913.
- [3] A. S. Alahmed, G. Cavraro, A. Bernstein, and L. Tong, “A Decentralized Market Mechanism for Energy Communities Under Operating Envelopes,” in *IEEE Transactions on Control of Network Systems*, vol. 12, no. 1, pp. 313-324, March 2025, doi: 10.1109/TCNS.2024.3466651.
- [4] C. Chen, S. Bose, T. D. Mount and L. Tong, “Wholesale Market Participation of DERAs: DSO-DERA-ISO Coordination,” in *IEEE Transactions on Power Systems*, vol. 39, no. 5, pp. 6605-6614, Sept. 2024, doi: 10.1109/TPWRS.2024.3352003.
- [5] A. S. Alahmed and L. Tong, “Dynamic Net Metering for Energy Communities,” in *IEEE Transactions on Energy Markets, Policy and Regulation*, vol. 2, no. 3, pp. 289-300, Sept. 2024, doi: 10.1109/TEMPR.2024.3354162.
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- [7] C. Chen, S. Bose, and L. Tong, “DSO-DERA Coordination for the Wholesale Market Participation of Distributed Energy Resources,” *Proc. of IEEE Power & Energy Society General Meeting*, 2023. **(IEEE PESGM Prize Conference Paper Award)**
- [8] A. S. Alahmed and L. Tong, “Resource Sharing in Energy Communities: A Cooperative Game Approach,” *2024 IEEE Power & Energy Society General Meeting (PESGM)*, Seattle, WA,

USA, 2024, pp. 1-5, doi: 10.1109/PESGM51994.2024.10688636. (**IEEE PESGM Best Paper Session**)

- [9] A. S. Alahmed, G. Cavraro, A. Bernstein, and L. Tong, "Network-Aware and Welfare-Maximizing Dynamic Pricing for Energy Sharing," *2024 IEEE 63rd Conference on Decision and Control (CDC)*, Milan, Italy, 2024, pp. 859-865, doi: 10.1109/CDC56724.2024.10885977.
- [10] M. Mousavi and M. Wu, "Transmission and Distribution Coordination Framework Using Parametric Programming: Optimal Pricing in The Distribution Systems ," *Hawaii International Conference on System Sciences (HICSS)*, 2023.
- [11] Coordinating Transmission and Distribution Systems Operations for Intensive DER Integration - Part I: A Parametric Programming Framework, under review for "*IEEE Transactions on Energy Markets, Policy and Regulation*".
- [12] Coordinating Transmission and Distribution Systems Operations for Intensive DER Integration - Part II: An Efficient Algorithm, under review for "*IEEE Transactions on Energy Markets, Policy and Regulation*".

Student Theses:

- [1] Cong Chen, "Future Power Systems Mechanism Designs: Storage and Distributed Energy Resource Integration," Cornell University, May 2024, (**2025 IEEE PES Outstanding Doctoral Dissertation Award and 2024 Cornell ECE Best Thesis Award.**)
- [2] Ahmed Alahmed, "Integration of Distributed Energy Resources: Optimal Decisions, Mechanism Design, and Aggregations," Cornell University, August 2024.
- [3] Mohammad Mousavi, "Distribution System Operator (DSO) Design for Distributed Energy Resources Market Participation", Arizona State University, May 2024.