



The Future of Markets and DERs: Providing Essential Grid Services and Managing Performance Risk

Final Project Report

M-44

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Power Systems Engineering Research Center

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Executive Summary

FERC Order 2222 mandates incorporation of distributed energy resources (DERs) in wholesale markets. With this new requirement, one main power systems change is the push towards not just DER integration but also the reliance on these resources to be able to provide essential grid services. Electricity markets, grid operations, and reliability requirements are designed for classical assets, not emerging assets with distinct characteristics, i.e., higher probability of failure, lower capacity firmness, and lower impact of failure. This project addresses the concern of DER integration from multiple fronts: a) effective aggregation and management of DERs to ensure their profitability and the quality of services provided by these aggregated resources, b) essential market and operational reform, and c) coordination of transmission and distribution services provided by DERs.

Part I: Intra-day DER Risk Assessment

Driven by climate goals and the transition to cleaner sources of energy, it is evident that the modern electric grid is undergoing a significant transformation in both its generation resource mix and demand-side management. The current reliability practices, however, were designed for classical assets and not fully suited for emerging resources. This part of the work presents intra-day risk assessment frameworks to complement existing practices and support the effective inclusion of DERs in wholesale electricity markets. Suitable decision-making frameworks to model uncertainty, risk, and correlation have been examined from perspective of various stakeholders in the DER management process.

In the first portion of the work, key challenges associated to participation of DERs in wholesale markets has been addressed from the perspective of a profit-maximizing Virtual Power Plant managing an aggregation of solar photovoltaic, electric storage, and residential load resources. It is shown that aggregation of DERs can perform comparably to conventional resources, despite their distinct uncertainty and variability characteristics. To address sequential decision-making under uncertainty, two modeling frameworks are explored: Markov Decision Processes (MDP) and robust optimization using Mixed Integer Linear Programming (MILP). The approaches are modeled to align with existing day-ahead and real-time market operations. While MDP modeling is conceptually consistent with sequential decision-making, it is impractical due to intrinsic assumptions about the system probabilities and computational intractability in VPP decision-making. In contrast, the MILP-based framework aligned with existing steady-state power system practices and demonstrates satisfactory performance. The modeling emphasizes risk preference of aggregators and time frames of rolling forecasts for solar and load resources. Detailed insights about modeling intricacies and associated computational requirements have been analyzed and presented in the report.

In the latter portion, intra-day situational awareness frameworks have been explored. Emerging resources such as behind-the-meter renewables and electric storage resources often lack full controllability and visibility to system operators managing the electric grid. To address this gap, an intra-day lookahead assessment framework is proposed that leverages historical performance of electric storage resources along with weather and price information. The framework predicts future state-of-charge (SOC) level and categorizes it into three zones: *low*, *medium*, and *high*. This

framework is aimed to assist system operators with downstream reserve procurement decisions and ensure reliability in the grid. A data-driven approach is employed to explore three statistical and machine learning models: (i) Seasonal ARIMA with eXogenous parameters (SARIMAX), (ii) Extreme Gradient Boosting (XGBoost), and (iii) Long Short-Term Models (LSTM). Detailed performance evaluation and comparison of the three models are presented.

Part II: DER and Smart Inverter Management for Coordinating Transmission - Distribution Services and Enhancing Distribution System Flexibility

The increasing penetration of residential roof-top photovoltaic (PV) and other Distributed Energy Resource (DER) units causes severe power quality issues including voltage violation and voltage unbalance within the distribution feeder and the transmission system. Legacy VAr devices, which were conventionally used to mitigate voltage violation issues within the distribution feeder, are incapable of providing a solution due to the fast voltage fluctuations caused by inverter-based resources. The sparsity and cost of installation and maintenance of these devices also prevent them from being an effective solution. The swift adoption of Electric Vehicles (EVs) also contributes to voltage unbalance issues, where the rapid change in demand due to multiple charging loads rules out conventional solutions to voltage balancing.

Apart from this, with the introduction of FERC order 2222, the inclusion of DER aggregators in the wholesale markets compounds on the previously mentioned problem, posing a challenge to the safe and reliable operation of the transmission and distribution systems. Due to the active nature of modern distribution systems and modeling complexities, the ISO has no visibility over the DS limits while making decisions on the DER aggregator's energy and ancillary service awards, leading to distribution system violations. Therefore, there is an emerging need for coordinating DER aggregators and transmission-distribution operations.

With the introduction of the IEEE 1547-2018 standards, Smart Inverters (SIs) are enabled to provide reactive power support using four different operational modes and voltage support using one active power operational mode. The fast control action, and the distributed and localized presence of these SIs enable them to provide a solution to all the shortcomings mentioned above. To maximize the efficiency of these SIs to mitigate the issues feeder-wide, an efficient DER scheduling tool is required. The consequent work presented investigates the popularly utilized reactive power and active power operational modes, by creating a DER scheduling tool utilizing a robust Distribution Optimal Power Flow (DOPF) model, the Current Voltage ACOPF (IVACOPF). Furthermore, a comprehensive Unified Mode Selection (UMS) framework is presented to optimally select the mode and set point of operation within the DER scheduling tool to minimize operational cost and mitigate voltage issues. The main objective of this work is to maximize deliverability subject to reliable and nominal distribution system operation.

Learnings from this work are then leveraged in improving distribution system hosting capacity, managing voltage violations and, effectively, improving overall distribution system flexibility. In this work, using statistical information obtained from different distribution system conditions and data-mining algorithms, an ISO-DSO-DERA coordination framework is proposed, which allows DER aggregators to participate in the wholesale electric market, having visibility into the distribution system and considering distribution system limitations. The performance of this

framework is compared with the case where the ISO has no visibility over the distribution system limits while making decisions on the aggregator’s energy and ancillary service awards. A detailed unbalanced AC optimal power flow based on IVACOPF model is utilized for emulating DSO-DERAs coordinated operations to manage distribution system limits while considering DERAs promised services to ISO. The effect of VAr support capability of roof-top PV unit SI is evaluated in increasing the distribution system flexibility to improve the deployability of the aggregators promised awards. The VAr capability of PV SIs is based on the IEEE 1547-2018 standard, formulated by mixed-integer linear constraints. An IEEE 118-bus system and unbalanced 240-bus distribution test system are used to compare performance of the different ISO-DSO-DERA coordination architectures and, transmission and distribution management during uncertain events.

Part III: Stable and Fair Uniform Price Allocations of Community Aggregation Gains in Retail Electricity Markets

The research, conducted at UC Berkeley, consists of two distinct works: a) Data-driven sizing of col-located storage for uncertain renewable energy, and b) Stable and fair market design in peer-to-peer electricity markets.

In the first work, a high-level stochastic steady-state model is proposed to analyze the value of col-located energy storage systems for wind power producers that participate in an electricity market through forward contracts and use storage to unlock access to capacity payments. In particular, the goal is to find optimal storage and contract sizing, as well as stationary operating policies for profit maximization in the long run. We propose a Markovian stylized model calibrated to actual wind power production that allows us to obtain limiting distributions of battery storage levels, assess the value of storage size and perform a sensitivity analysis on key parameters such as contract prices, capacity payments and storage efficiency. We develop the case with contracts of constant price, outline how this model can be extended to a variable-price setting and discuss potential challenges in that avenue.

The advent of differentiated prices for consuming (buying) and injecting (selling) electricity at the residential level promotes the emergence of local peer-to-peer electricity markets for prosumers, which can deliver savings to participants as long as an attractive cost sharing mechanism can be designed. Building on cooperative game theory models that have been proposed in the literature, we define the uniform price core, a class of desirable distribution of savings in this context, and prove constructively that it is not empty. We propose the shadow price imputation, a computationally efficient stable uniform price imputation, which we show to be equivalent to a dual imputation in the sense of cooperative linear production games. In the second part of the chapter, we compare the shadow price imputation to other imputations in the uniform price core through the lens of fairness. To overcome the challenge of tractability for larger numbers of participants, we extend an existing sampling methodology and apply it to optimization problems devised to obtain a fair imputation. The long-term incentive implications for different stakeholders, as well as a generalization to a stochastic case where the uncertainty in renewable production and local demand is considered, are also discussed. We present theoretical results and numerical experiments and examples to illustrate our approach.

Project Publications:

- [1] T. Roy, A. K. Jana, and K. W. Hedman, "Optimization of Aggregated Energy Resources using Sequential Decision-making," in *2022 North American Power Symposium (NAPS)*, 2022, pp. 1–6. doi: 10.1109/NAPS56150.2022.10012186.
- [2] T. Roy and K. W. Hedman, "Risk Quantification with Management of Aggregated Energy Resources," in *2024 IEEE Power & Energy Society General Meeting (PESGM)*, 2024, pp. 1–5. doi: 10.1109/PESGM51994.2024.10689045.
- [3] T. Roy and K. W. Hedman, "A Sequential Decision-making Framework for Management of Aggregated Energy Resources," - *Under preparation*.
- [4] T. Roy and K. W. Hedman, "Intra-day Lookahead Models for Energy Storage Resources Using Time Series Prediction," - *Under preparation*.
- [5] H. K. A. Parthasarathy, Z. Soltani and M. Khorsand, "Operational DER Scheduling Tool for Unbalanced Distribution Systems Considering Watt-VAr Controllers of PV Smart Inverters" 2023 NAPS, NC, USA, pp. 1-6.
- [6] H. K. A. Parthasarathy, M. Ghaljehei, Z. Soltani and M. Khorsand, "Qualification and Disqualification of Aggregator's Energy and Ancillary Service Awards in Wholesale Markets", Submitted for review, IEEE Open Access Journal of Power and Energy.
- [7] H. K. A. Parthasarathy, Z. Soltani and M. Khorsand, "Unified Mode Selection Framework for Real-Time VAr Optimization Tool in Unbalanced Distribution Systems" , To be submitted.
- [8] T. V. Zuluaga and S. S. Oren, "Data-Driven Sizing of Co-Located Storage for Uncertain Renewable Energy," in *IEEE Transactions on Energy Markets, Policy and Regulation*, vol. 1, no. 4, pp. 348-359, Dec. 2023, doi: 10.1109/TEMPR.2023.3277844.
- [9] T. V. Zuluaga and S. S. Oren, "Cost Sharing Mechanism with Statistical Learning for Peer-to-Peer Energy Trading," 2023 IEEE Power & Energy Society General Meeting (PESGM), Orlando, FL, USA, 2023, pp. 1-5, doi: 10.1109/PESGM52003.2023.10253145.
- [10] T. V. Zuluaga and S. S. Oren, "Sizing co-located storage for uncertain renewable energy sold through forward contracts," arXiv preprint arXiv:2207.12619, 2022.

Student Theses:

- [1] T. V. Zuluaga, "Optimization of electricity systems under uncertainty," Ph.D. dissertation, UC Berkeley, 2024.
- [2] H. K. A. Parthasarathy, "A Unified Mode Selection Framework for DER Scheduling Tool Considering Unbalanced Distribution Systems" Order No. 31336937, Arizona State University, United States -- Arizona, 2024. (Student is pursuing a PhD in Power and Energy Systems at Arizona State University)
- [3] T. Roy, "Modeling and Characterization of Distributed Energy Resources in Electricity Markets". PhD dissertation. Expected Graduation: 2026.