



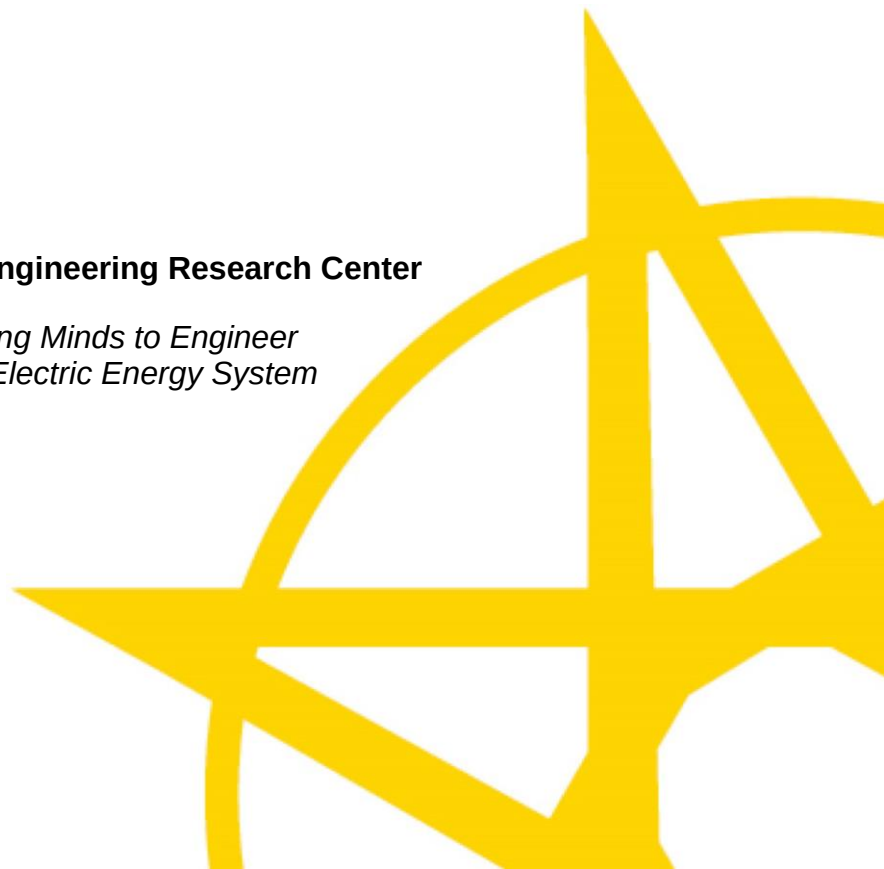
Who are controlling the DERs? Increasing DER hosting capacity through targeted modeling, sensing, and control

Final Project Report

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Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Executive Summary

Distributed energy resources (DERs) offer many opportunities for providing grid services but may also cause issues in distribution grid operations. The overall goal of this project was to develop modeling, analysis and optimization techniques for systems that improves our understanding and ability to control systems with many distributed energy resources (DERs). These new techniques help us understand how DERs interact with the electric distribution grid, and how to assess the variability, control opportunities and sensing needs that arise with higher penetrations for DERs.

More specifically, the project had three main goals, namely to (1) better characterize the uncertainty associated with DER power injections and control, (2) assess the optimal placement of voltage sensors in the distribution grid and (3) identify secure ranges for DER control by third-party aggregators. Progress towards these goals was achieved in three integrated tasks, with frequent interactions and discussions between the team members. Given the distinct goals of each task, the research findings of this report is presented in three separate parts corresponding to the three tasks of the project. The goals and research findings of each task is included below.

Part I: From load modeling and uncertainty characterization to distribution system operational scheduling and optimal inverter control

Part I includes two chapters. First chapter presents approaches for load modeling and uncertainty characterization. Second chapter proposes two advanced approaches for distribution system operational scheduling and DER control and optimization.

Load modeling and uncertainty characterization: This project designed and developed load forecasting and advanced aggregation strategies based on machine learning approaches. Artificial Neural Network is used for aggregated load forecasting while the forecast errors were evaluated and characterized as uncertainty of forecasted load. Fitness of load uncertainty to known probability distributions were checked by Shapiro–Wilk test. Next, to enable assessment of demand side flexibility, appliance-level load monitoring and forecasting techniques were investigated. The knowledge of distribution load characteristics enables more effective management of DER-enriched distribution systems. For example, knowing the percentage of air conditioning load assists operators in understanding load flexibility (for direct load control or other demand response schemes). As another example, discovery of connected electric motor load enables better assessment of voltage stability concerns, i.e., fault-induced delayed voltage recovery. Another example is home energy management, which is performed at the appliance-level. To this end, the team has developed an optimization approach along with artificial intelligence (AI)-based approaches, namely conditional hidden semi-Markov model. The accuracy of these models was tested using actual historical smart meter data.

Distribution system operational scheduling and optimal DER control: This project proposes two distribution operational scheduling frameworks based on two different unbalanced three-phase distribution AC optimal power flow models: A) a novel current-voltage rectangular approach, and B) a two-stage second-order cone programming-based approach. Both of these algorithms accurately capture unique characteristics of distribution systems, namely mutual impedances, single-phase to three-phase feeders and laterals, and unbalanced nature. We tested both of these algorithms using data of an actual distribution feeder and corresponding load and PV generation from an electric utility. The comparison of power flow results of these models with OpenDSS

(EPRI’s distribution power flow analysis tool) confirms the accuracy and effectiveness of these algorithms in capturing unique characteristics of distribution systems. Moreover, both these proposed unbalanced AC optimal power flow models are enhanced to account for Volt-Var controller of PV smart inverters based on the characteristic that is outlined in IEEE Standard 1547-2018. Moreover, these algorithms are further enhanced to optimize droop characteristics of Volt-Var controllers within the allowable range, which is set by IEEE Standard 1547-2018. The results of testing these algorithms on an actual distribution feeder show that optimizing Volt-Var controller settings and droop characteristics of smart inverters substantially enhance distribution voltage management and reduces the need for active power curtailment of DERs to maintain voltage within the acceptable range as set by ANSI standard. This is a critical contribution of this project as distribution system voltage management is deemed to be more challenging with high penetration levels of DERs.

Project Publications:

- [1] Mingyue He and Mojdeh Khorsand, “Residential Appliance-level Consumption Modeling and Forecasting via Conditional Hidden Semi-Markov Model”, *the 54th North American Power Symposium*, 2022.
- [2] Mingyue He, Zahra Soltani, Mohammad Ghaljehei, Masoud Esmaili, Shanshan Ma, Mengxi Chen, Mojdeh Khorsand, Raja Ayyanar, and Vijay Vittal, “A SOCP-based ACOPF for Operational Scheduling of Three-phase Unbalanced Distribution Systems and Coordination of PV Smart Inverters,” *IEEE Transactions on Power Systems*, under review.
- [3] Zahra Soltani, Shanshan Ma, and Mohammad Ghaljehei, “Optimal Scheduling of Distributed Energy Resources Considering Volt-Var Controller of PV Smart Inverters,” *the 11th Bulk Power Systems Dynamics and Control Symposium*, July 2022.

Student Theses:

- [1] Mingyue He, “Distribution system operation and control enhancement: from load forecasting and DER aggregation to distribution operational scheduling,” *PhD Dissertation, Arizona State University*, expected May 2024.
- [2] Zahra Soltani, “Sensor Enabled Advanced Distribution Management System: From Topology Processor and State Estimation to Distributed Energy Resources Scheduling,” *PhD Dissertation, Arizona State University*, expected May 2023.

Part II: Bilevel Optimization Approaches for Locating Sensors in Distribution Systems

In **Part II**, we developed an algorithm for finding optimal sensor locations and alarm thresholds for rapid identification of voltage violations. This algorithm solves a bilevel optimization problem which minimizes the number of sensors and the number of false alarms (upper-level problem) while making sure that there are no voltage violations that go undetected (lower-level problem). Since this bilevel problem is difficult to solve directly, we developed several approaches for addressing its computational challenges. We first addressed the power flow nonlinearities in the lower-level problem by developing conservative linear approximations of the power flow equations. These approximations provide overestimates and underestimates of the nonlinear power flow equations over the relevant operational range. By replacing the nonlinear power flow equations with these conservative linear approximations, we can ensure that the resulting sensor

locations and alarm thresholds are sufficient to identify any constraint violations that might occur for any power injections within a specified range of power injection fluctuations. The accuracy of these conservative linear approximations is closely connected to the quality of the sensor locations and alarm thresholds that result from solving the reformulated bilevel optimization problem. We therefore spent significant effort in developing methods for improving their accuracy. These methods are discussed in detail in this report.

Even after replacing the power flow equations with these conservative linear approximations, the sensor placement problem remains computationally challenging due to its bilevel nature. As we show with several numerical test cases, standard techniques for reformulating the sensor placement problem to a single-level formulation that can be addressed with existing solvers yield optimization problems that are only tractable for small test cases. Accordingly, the team exploited structure specific to this problem to obtain single-level mixed-integer programming formulations that can be solved with commercial software packages like Gurobi. Key insights in these reformulations include the importance of discretizing the sensor thresholds and a tailored dualization approach that avoids introducing unnecessary additional discrete variables, as would be required using traditional methods for bilevel problems.

The resulting sensor placement reformulations require substantially less computational time than standard reformulation techniques, thus enabling us to scale up to problems with tens to hundreds of buses. Furthermore, we developed extensions to these reformulations that consider the possibility of multiple network topologies, with the results still showing strong computational scalability characteristics.

To improve the sensor placements resulting from this bilevel problem formulation, we developed a post-processing technique that reduces the number of false alarms. Using an approximate gradient approach, this post-processing technique adjusts the sensor thresholds to make them less conservative while not introducing false negatives (missed alarms). The combination of the bilevel problem reformulation and this post-processing technique allows us to compute sensor locations and alarm thresholds that have a small number of false alarms and no missed alarms, as validated numerically using out-of-sample testing.

Next steps for this work include modeling extensions to consider sensors with more general capabilities and more detailed representations of the distribution network and associated devices. Complementing the test cases considered in this report, we also aim to demonstrate the developed techniques on actual large-scale distribution system data sets in order to assess their scalability and quality of the resulting solutions. Finally, we intend to apply the mathematical reformulation techniques developed in this project to other challenging optimization problems beyond the sensor placement problem considered in this report.

Project Publications:

- [1] P. Buason, S. Misra, and D.K. Molzahn, "A Sample-Based Approach for Computing Conservative Linear Power Flow Approximations," *Electric Power Systems Research*, vol. 212, no. 108579, November 2022. Presented at 22nd Power Systems Computation Conference (PSCC), June 27 - July 1, 2022.
- [2] P. Buason, S. Misra, and D.K. Molzahn, "A Data-Driven Method to Identify Critical Locations for Sensors in Distribution Grids," in preparation.

Student Theses:

- [1] Paprapee Buason, “Addressing Power Flow Nonlinearities in Bilevel Optimization Problems with Applications to Optimal Sensor Placement in Electric Distribution Systems,” *PhD Dissertation, Georgia Institute of Technology, School of Electrical and Computer Engineering*, December 2024 (expected).

Part III: Identifying Secure Operation Ranges For DER Control by Third-Party Aggregators

In **Part III**, we focused on challenges associated with coordinating control activation from DERs across multiple different entities, including third-party DER aggregators who are able to dispatch the DERs through contracts with DER owners, the distribution system operator (DSO) who is in charge of making sure that no grid constraints are violated in the distribution grid, and the independent system operator who needs to contract flexibility services from the third-party aggregator while respecting distribution grid constraints. Our research takes the perspective of a DSO who aims to identify a secure flexibility region for DER active power control within the distribution grid. We envision that the this secure flexibility region can be used as feeder-level capacity constraints in the real-time market clearing to ensure that DER flexibility provided by third-party aggregators will not violate any distribution level constraints. Specifically, the ISO could use these flexibility ranges to provide a simplified view of distribution grid constraints when clearing bids from DER aggregators with resources located inside the distribution grid. This research thus proposes one solution for integration of aggregated DER resources in electricity market clearing, as mandated by FERC Order 2222.

The key innovation of this work with respect to existing literature is that we allow entities other than the distribution system operator to make decisions on how to dispatch individual DERs within the feeder. Existing work has either assumed that the DSO can directly dispatch active power from DERs or have provided flexibility ranges for each DER. However, such assumptions place unrealistic assumptions on coordination and information exchange between third-party aggregators and DSOs, such as the sharing of grid models or confidential bid information. These problems become particularly acute when there is more than one aggregator with resources located inside the feeder. To circumvent these issues, we assume that third-party aggregators decide how individual DERs are activated to achieve a certain control outcome, without further coordination with the DSO or other aggregators within the feeder. The DSO, on the other hand, are only able to provide limits on the total amount of DER control activation the feeder is able to provide. The goal of our research is to identify how large this total amount is allowed to be.

To identify secure flexibility ranges for this case, we have to assume that these other entities (such as third-part aggregators) could potentially choose dispatch DERs in a harmful way. We therefore formulate and solve the problem as an adversarial bilevel program, where the upper level problem (representing the DSO) maximizes the range of flexibility available from the feeder, while the lower level problem (representing the joint control activation across all DERs) enforces that the maximum and minimum achievable voltage magnitudes remain within safe bounds. Part III of this report presents our formulation of a linearized bilevel problem, discusses how to obtain a tractable single level reformulation and provides numerical results.

As part of our research, we identified that the secure flexibility region can be significantly increased by incorporating some simple rules for DER control activation:

- First, we identify that we need to ensure that **all DERs are controlled in the same direction**, i.e., the DERs can either increase or decrease their set-points relative to the current operating point. This prevents situations in which some DERs increase their active power injections while others decrease their injections, leading to potential voltage problems even with very small total active power control.
- Second, we evaluate the impact of different modes of reactive power control including setting a constant reactive power injection, determining the power factor or controlling the active power droop. We identify that several different modes can provide good results. However, it is vitally **important that the DSO decides how reactive power is controlled**, rather than allowing individual DERs to choose (potentially harmful) reactive power set-points.
- To link with the work done in Task 2 and 3, we also considered how limited access to measurements and uncertainty regarding the current operating point of the system can be reflected in this optimization problem. In our case study, we observe that **it is possible to obtain wide flexibility ranges, even with limited real-time observability**, although further investigations are needed to confirm these results more widely.

Beyond the main conclusions above, we have also run experiments to confirm that the accuracy of our linearized optimization model is acceptable.

Immediate next steps for this work include identification of the most practical DER reactive power control modes and more detailed discussion of the case without real-time measurements. More significant, but practically important aspects include the consideration of multi-period problems (i.e., how flexibility ranges may change as DER control capability and system set-points evolve over time) as well as forecasting of flexibility ranges for future operating periods to support, e.g., day-ahead market clearing. We would also like to test our methods on realistic distribution feeders to address possible issues associated with data access and confidential information.

Project Publications:

- [1] K. Girigoudar and L. A. Roald, "Linearized Three-Phase Optimal Power Flow Models for Distribution Grids with Voltage Unbalance," *IEEE Conference on Decision and Control (CDC)*, December 2021, pp. 4214-4221, doi: 10.1109/CDC45484.2021.9683780.
- [2] K. Girigoudar and L. A. Roald, "Identifying Secure Operating Ranges for DER Control using Bilevel Optimization," *submitted*.

Student Theses:

- [1] Kshitij Girigoudar. "Optimization of Unbalanced Distribution Grid Operations using Distributed Energy Resources". *Phd Dissertation, University of Wisconsin Madison, Department of Electrical and Computer Engineering*, August 2022