



Robust and Decentralized Operations for Managing Renewable Generation and Demand Response in Large-Scale Distribution Systems Simulations

Final Project Report

M-35

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

The final report has six chapters. The content of the chapters is summarized below.

1. Chapter 1 develops a robust optimization framework for demand response management. In particular, our model considers the realization uncertainty in demand reduction by a DR resource, which depends on the dispatch decision of the DR resource. This type of intrinsic decision-dependent uncertainty has not been fully recognized and modeled in the DR resource management software. Our work provides a first work in this direction.
2. Chapter 2 proposes a distributed algorithmic framework for solving AC optimal power flow (AC OPF). AC OPF is at the core of power system operations. As the number of distributed generation units and flexible load increases, it is becoming more and more important for the system operators to have the ability to solve AC OPF in a decentralized way. This chapter proposes a rigorous distributed algorithm for solving AC OPF based on the recent progress in convexification of power flow equations. The proposed algorithm shows promising performance in solving real-world sized systems in distributed fashion.
3. Chapter 3 studies the voltage stability issues in the distribution systems. We propose a novel voltage stability-constrained optimal power flow (VSC-OPF) model utilizing a recently proposed sufficient condition on power flow Jacobian nonsingularity. We show that this condition is second-order conic representable when load powers are fixed. Through the incorporation of the convex sufficient condition and thanks to the recent development of convex relaxation of OPF models, we cast a VSC-OPF formulation as a second-order cone program (SOCP). An approximate model is introduced to improve the scalability of the formulation to larger systems. Extensive computation results on MATPOWER and NESTA instances confirm the effectiveness and efficiency of the formulation.
4. Chapter 4 constructs an analytic tool based on a model that captures the interaction between pricing and investment. In contrast to previous approaches, this technique allows consistently comparing portfolios of rates while enabling researchers to model with a significantly greater level of detail the supply side of the sector. A key theoretical implication of the model that underlies this technique is that, by properly updating the portfolio of tariffs, a regulator could induce the welfare maximizing adoption of distributed energy resources and enrollment in rate structures. We develop an algorithm to find globally optimal solutions of this model, which is a nonlinear mathematical program. The results of a computational experiment show that the performance of the algorithm dominates that of commercial non-linear solvers. In addition, to illustrate the practical relevance of the method, we conduct a cost benefit analysis of implementing time-variant tariffs in two electricity systems, California and Denmark. Although portfolios with time-varying rates create value in both systems, these improvements differ enough to advise very different policies. While in Denmark time-varying tariffs appear unattractive, they at least deserve further revision in California. This conclusion is beyond the reach of previous techniques to analyze rates, as they do not capture the interplay between an intermittent supply and a price-responsive demand.

5. In Chapter 5, we develop a technique based on a pricing model that has as a fundamental building block the consumer utility maximization problem. Because researchers do not have to limit themselves to problems with unique solutions, this approach significantly increases the flexibility of the model and, in particular, addresses the limitations of the technique we develop in the first chapter. This gain in flexibility decreases the practicality of our method since the underlying model becomes a Bilevel Problem. To be able to handle realistic instances, we develop a decomposition method based on a non-linear variant of the Alternating Direction Method of Multipliers, which combines Conic and Mixed Integer Programming. A numerical experiment shows that the performance of the solution technique is robust to instance sizes and a wide combination of parameters. We illustrate the relevance of the new method with another applied analysis of rate structures. Our results highlight the value of being able to model in detail distributed energy resources. They also show that ignoring transmission constraints can have meaningful impacts on the analysis of rate structures. In addition, we conduct a distributional analysis, which portrays how our method permits regulators and policy makers to study impacts of a rate update on a heterogeneous population. While a switch in rates could have a positive impact on the aggregate of households, it could benefit some more than others, and even harm some customers. Our technique permits to anticipate these impacts, letting regulators decide among rate structures with considerably more information than what would be available with alternative approaches.
6. In Chapter 6, we conduct an empirical analysis of rate structures in California, which is currently undergoing a rate reform. To contribute to the ongoing regulatory debate about the future of rates, we analyze in depth a set of plausible tariff alternatives. In our analysis, we focus on a scenario in which advanced metering infrastructure and home energy management systems are widely adopted. Our modeling approach allows us to capture a wide variety of temporal and spatial demand substitution patterns without the need of estimating a large number of parameters. We calibrate the model using data of appliance ownership, census household counts, weather patterns, and a model of California's electricity network. The analysis shows that the average gains of implementing time-varying rates with respect to a simple flat rate program are rather mild, not greater than 2 dollars per month, even in the scenario in which volumetric charges are allowed to vary freely from hour to hour. Our results also show that factors such as the presence of an air conditioning system and the exterior temperature profile can have a meaningful impact on the surplus gains that different rates generate on households. These two results combined suggest that defaulting all residential customers into a time-of-use rate structure, which is the current path California is following for the residential sector, may not be an optimal strategy. Targeting different rates to households with different appliance stocks and in different locations will likely be a superior policy.

Project Publications:

- [1] B. Cui and A. Sun. "A New Voltage Stability-Constrained Optimal Power Flow Model: Sufficient Condition, SOCP Representation, and Relaxation," accepted for publication in *IEEE Transactions on Power Systems*, 2018.

- [2] H. Chen, A. Sun, and S. Deng. “Robust Demand Response Portfolio Management under Decision-Dependent Uncertainty,” to be submitted, *INFORMS Journal on Optimization*, 2018.
- [3] K. Sun and A. Sun. “Distributed Algorithms for Solving AC OPF Using SOCP Relaxation,” to be submitted, *IEEE Transactions on Power Systems*, 2018.
- [4] F. Castro and D. Callaway, “Optimal electricity tariff design with demand-side investments,” in preparation.

Student Theses:

- [1] F. Castro. *On Rate Design in Modern Electricity Sectors*, PhD Dissertation, University of California, Berkeley.