Final Scientific/Technical Report

University of Colorado Boulder
Final Scientific/Technical Report
Intelligent System Partitioning
for Agent-Based Security
Constrained Optimal Power
Flow
DE-AR0001082

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Project Team Members	University of Texas at Austin
Project Title:	Intelligent System Partitioning for Agent-Based Security Constrained Optimal Power Flow
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Public Executive Summary

This project developed scalable, computationally efficient algorithms to solve realistic large-scale power system optimization problems as part of a larger series of competitions run by ARPA-E. These problems are important because the secure and reliable operation of the power grid, especially under increased uncertainty and variability, is growing increasingly challenging. The economic feasibility of the proposed methods developed by our team is quite low, considering it's a purely software-based solution to operate power grids more efficiently. The technical effectiveness, as evidenced by our performance in the competition, balances heuristics and approximations to provide a tradeoff between speed and accuracy.

The power grid is due for advancements in software as operational reliability is increasingly threatened. Better computational tools to operate these grids and assets can benefit the public by providing access to reliable power in a robust manner. Our team's approach leveraged multiple techniques surrounding reasonable approximations of physics, data-driven methods to reduce the complexity of the problem and uncover patterns in the chosen operational strategies, and techniques to distribute computations, utilizing parallel computing.

Acknowledgements

The project team would like to thank ARPA-E for the financial support on this project and the Pacific Northwest National Laboratory for being so helpful and responsive with assistance with the supercomputer.

Accomplishments and Objectives

This award allowed the University of Colorado Boulder and the University of Texas at Austin to demonstrate a number of key objectives. The focus of the project was on building a software-based platform to solve complex, large-scale security constrained optimal power flow (SCOPF) problems on both synthetic and industry networks. The initial funding ($249,178) was used to participate in Challenge 1 of the ARPA-E Grid Optimization (GO) competition, and as our team performed well, we were awarded prize money in the form of additional funding to participate in Challenge 2 of the competition.

A number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project (e.g. for Challenge 1). Note that *many* different techniques were used in the development of our entry into the competition, and our final submissions in both Challenge 1 and Challenge 2 of the competition also varied in algorithmic approach. The actual performance against the stated milestones is summarized here:

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
Task 1: Application of the intelligent system partitioning algorithm to the agent-based SCOPF framework. CU will extend the methodology to an agent based distributed framework.	An algorithm based on the proposed in the initial proposal was one of the methods tried throughout the competition, in addition to various other decomposition methods. In particular, Benders decomposition ended up working well here. Note that the proposal was written before the team had access to the datasets and networks provided by ARPA-E, and thus it was challenging to know exactly what algorithm would perform well. Based on this initial stage, we decided to go in a different direction with our entry to the competition.
Task 2: Development of novel constraint relaxation techniques for complementarity constraints. This task will be performed concurrently with Tasks 1 and 3, and the results of this task will be used in Task 4.	Various constraint relaxation techniques were experimented with, including those for complementarity constraints. In particular, the PV/PQ switching constraints.

Task 3: Extension of the distributed agent-based SCOPF solver to include AC power flows and familiarization with the GO submission interface. The algorithm will be able to take in variable subproblem sizes as determined by the algorithm in Task 1.	We have developed both DC-based and AC-based power flow code. In the initial stages of the competition, a rule-based strategy was used where smaller networks ran the AC-power flow formulation and larger networks, to save on computational burden, ran the DC-power flow formulation. In later stages of the competition, we used various combinations of AC and DC based strategies and discussed further in our publications under this project. In addition, other approximations were experimented with (as detailed in conference paper [2], for example).
Task 4: Combination of the results of Tasks 1, 2, and 3 into a single framework. Scalability testing on publicly available test networks (i.e., IEEE test networks, NREL's synthetic test networks, etc.). The proposed algorithm will be tested on a series of transmission networks to ensure that the technical performance goals in Sec. 1.3 are consistently met.	The results from approximations, decomposition formulations, and relaxation techniques were combined in our final submissions for Challenge 1 and Challenge 2. In each case, multiple algorithms were used in the final submission that depended on time available, network size, etc. The test networks provided by ARPA-E were used in the scalability testing.

Our team performed extensive testing using the given datasets on the provided PNNL platform as well as our local machines at CU Boulder. Three peer-reviewed publications and one preprint were produced, which are listed under the Project Outputs section.

Project Activities

The project developed a two-stage approach to the security constrained optimal power flow problem. In the first stage a linearization of the power flow equations was applied, resulting in a mixed integer linear programming problem. This was used to determine the integer control variables before a non-linear programming approach was used to determine the continuous variables which used the full AC power flow constraints. This approach was chosen to balance the importance of including the unit commitment binary variables with the penalty of finding solutions which were not AC feasible. Additionally, data-driven methods were used to reduce the set of contingencies considered. The best success was found using artificial neural networks to predict contingency importance based on network and contingency parameters (e.g. rating of component, number of buses, bus voltage). Decomposition methods, such as benders decomposition, were explored but not utilized in the final event due to inconsistent performance between different networks and loading cases. The final result was a fast and robust code, which performed consistently across different networks and reliably finished within the 5 minute time interval. However, the linearized approach we took in the first stage caused sub-optimal performance in some networks, where the chosen generators could not be used due to network constraints. This approach performed similarly in the longer division because the linearized approach was so fast.

Project Outputs

A. Journal Articles

[1] C. Crozier, K. Baker, and B. Toomey, "Feasible region-based heuristics for optimal transmission switching," Sustainable Energy, Grids, and Networks, vol. 30, pp. 100628, Jun. 2022.

B. Papers

[1] C. Crozier, K. Baker, Y. Du, J. Mohammadi, and M. Li, "Data-driven Contingency Selection for Fast Security Constrained Optimal Power Flow," 2022 17th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Jun. 2022.

[2] M Li, Y Du, J Mohammadi, C Crozier, K Baker, and S Kar, "Numerical Comparisons of Linear Power Flow Approximations: Optimality, Feasibility, and Computation Time," IEEE Power and Energy Society General Meeting, Jul. 2022.

[3] H. Bazrafshan, K. Baker, and J. Mohammadi, "Computationally Efficient Solutions for Large-Scale Security-Constrained Optimal Power Flow," arXiv preprint arXiv:2006.00585v1, 2020.

C. Status Reports

N/A

D. Media Reports

N/A

E. Invention Disclosures

N/A

F. Patent Applications/Issued Patents

N/A

G. Licensed Technologies

N/A

H. Networks/Collaborations Fostered

In partnership with the national electric and gas grid operator in Portugal, we are expanding the applications of this line of research to solving large-scale grid planning problems to modernize Portuguese's grid. The learnings from GO 2 competition have served as the guiding principles for developing this planning tool.

I. Websites Featuring Project Work Results

N/A

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

N/A

K. Awards, Prizes, and Recognition

Top Ten Performing Team in the ARPA-E Grid Optimization Competition Challenge 1

Top Five Performing Team in the ARPA-E Grid Optimization Competition Challenge 2

Follow-On Funding

Table 2. Follow-On Funding Received.

Source	Funds Committed or Received
ARPA-E Grid Optimization Competition Challenge 3	$400,000