Final Scientific/Technical Report

gollnlp and *magos*

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Public Executive Summary

In 2018, the Advanced Research Project Agency – Energy (ARPA-E) launched the Grid Optimization Competition (GOC) [1], a series of competitive challenges intended to accelerate innovation in decision support software used to schedule power grid operations, making them as efficient as possible, while respecting operational constraints of power equipment and operational security. This report covers the participation of teams led by the Lawrence Livermore National Laboratory (LLNL) in Challenge 1 and Challenge 2 of the competition.

Each challenge had an approximate duration of 1 year—Challenge 1 taking place in 2019 and Challenge 2 in 2021—and each consisted of 4 Competitive Events; 3 Trial Events and 1 Final Event. At Competitive Events, participants were ranked based on the performance of their approaches on a large set of realistic cases for multiple divisions, corresponding to different walltime limits for algorithm execution, aggregate performance metrics, and features additional features. Top performers at Final Events, and some Competitive Events, were awarded cash prizes or follow-on funding prizes.

Challenge 1 asked participants to develop solution approaches for a near-real time formulation of the security-constrained alternating-current optimal power flow problem (NRT-SCACOPF). The most complicating feature of NRT-SCACOPF with respect to current industry approaches is a much more realistic model of how generators' controllers react, following a sudden unplanned outage, to keep the network from falling into imbalances (frequency drop, automatic generation control) and maintaining the bus voltages within nominal values (local voltage controllers, PV/PQ switching). The LLNL-led team *gollnlp*, led by Dr. Cosmin Petra adopted an approach based on state-of-the-art theory and computational tools for nonlinear programming and judicious use of high-performance computing (HPC). Notable developments by the team include highly effective projection and crashing of complementarity equations coupled with advanced re-starting techniques for the interior-point method of Ipopt [2], empirical zero-order surrogate models to efficiently optimize over the impactful contingencies, and an asynchronous parallel scheduler/algorithm. We first developed a prototype Julia/JuMP [3, 4] parallel computing code using Ipopt [2] as the backend optimization solver for the subproblems. Later in the Challenge 1, we ported the framework to an HPC C++ implementation and performed a couple of rounds of testing, tuning, and bug fixing. The approach was ranked first in all Divisions of Challenge 1 and it accounted for over 58% of all best scores in individual cases. Details of *gollnlp* are presented in Chapter 1.

Challenge 2 asked participants to develop solution approaches for a next-snapshot (5-10 minutes ahead) formulation of the security-constrained alternating-current optimal power flow problem (NS-SCACOPF). These formulations are typical in industry, but in Challenge 2 they included additional aspects not typically considered in industry, such as explicit reactive dispatch and optimal transmission switching. The LLNL-led team *magos*, led by Dr. Ignacio Aravena build an approach incrementally throughout the Trial Events. First, the approach modeled only continuous variables and simplified the model for operations following sudden outages. Later, we incorporated integer variables in the approach using a rounding heuristic, and we implemented an ADMM-based decomposition approach for handling outages. Finally, we implemented optimal transmission switching using non-linear relaxations

and rounding. The developed approach perform among the average of participants in Trial Events and did not attain a good performance in the Final Event due to a parser error. Details of *magos* are presented in Chapter 2.

The techniques developed in both challenges, especially in Challenge 1, have the potential for transfer to industry, increasing the efficiency and security of power grid operations, resulting in overall savings and increased quality of service for final US electricty consumers.

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Chapter 1

ARPA-E GO Competition Challenge 1 – gollnlp team

1.1 Accomplishments and Objectives

This award allowed the LLNL-lead team *gollnlp* to develop a state-of-the-art approach for near-real time formulation of the security-constrained alternating-current optimal power flow problem (NRT-SCACOPF) put forward by the ARPA-E GOC Challenge 1 organization team [5]. The *gollnlp* approach combines state-of-the-art nonlinear optimization and computational mathematics, with surrogate optimization algorithms and specialized scenario reduction methods. This approach was ranked first in all divisions of ARPA-E GOC Challenge 1 Final Event, attaining the best performance of any team in more than 58% of the test cases in the Final Event.

A number of tasks and milestones were laid out in Attachment 2, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized in Table 1.1.

Table 1.1: Key Milestones and Deliverables

Tasks	Milestones and Deliverables
Task 1: Registration	Register for Challenge 1 of the GO Competition on the competition website (https://gocompetition.energy.gov/) **Actual Performance:** (January 16, 2019) Registration of all team members completed and approved by ARPA-E.
Task 2: Sandbox submission	Produce a valid Sandbox submission. **Actual Performance:** (February 1, 2019) Submitted initial valid approach to Sandbox.
Task 3: Trial 1 Event	Participate in the Trial 1 Event of Challenge 1; results must be displayed on the leaderboards. **Actual Performance:** (April 15, 2019) Approach for Trial 1 Event submitted before deadline. Trial 1 leaderboards made public by ARPA-E on May 22, 2019.
Task 4: Trial 2 Event	Participate in the Trial 2 Event of Challenge 1; results must be displayed on the leaderboards. **Actual Performance:** (July 19, 2019) Approach for Trial 2 Event submitted before deadline. Trial 1 leaderboards made public by ARPA-E on August 21, 2019.
Task 5: Final Event	Participate in the Final Event of Challenge 1; results must be displayed on the leaderboards. Results must be certified. **Actual Performance:** (October 30, 2019) Approach for Final Event submitted before deadline. Certification of results completed by January 25, 2020. Final Event leaderboards made public by ARPA-E on February 12, 2020.

1.2 Project Activities

The official NRT-SCACOPF formulation for ARPA-E GOC Challenge 1 [5] included nonlinear alternating current power flow equations for normal operation (*base case*) and stationary operation following a pre-specified set of single-element outages (*post-contingency*). The formulation modeled transmission lines; transformers and phase shifters tap with fixed settings; fixed shunts; switched shunts with continuous decisions; fixed loads; and generators with automatic generation control (AGC) and voltage control. All elements must be operated within technical limits in the base case and post-contingency, and the transition between base case and post-contingency is mediated only by the action of the controllers at generators: generators adjust their active power production setpoint following coordinated AGC in response to a system-wide signal (frequency), and their reactive power production following local voltage regulation, that is, they try to maintain the voltage set in the base case in the post-contingency state by injecting/withdrawing reactive power, swithching the buses from PV mode (set active power and voltage) to PQ mode (set active and reactive power) whenever maintaining the voltage is not possible (PV/PW switching). Modeling both AGC and PV/PQ switching is non-standard in the industry and no effective technique to address them was known at the start of Challenge 1. Similarly, the use of nonlinear power flow equations is traditionally restricted to the base case in industry and contingencies are modeled using a linear approximation known as *DC power flow*.

In order to develop an effective solution for this problem, the *gollnlp* team worked in stages. First, we developed a Julia/JuMP prototype implementation of all NRT-SCACOPF constraints, including a complementarity formulation for AGC and PV/PQ switching, in which we solved the base case along with a small group of contingencies—selected by largest component size, flow, or production—and the remaining contingencies where only considered via proxy penalties on base case quantities. AGC and PV/PQ complementarity constraints where smoothed and enforced gradually to avoid numerical ill-conditioning. The subproblems were solved using Ipopt compiled with MKL and HSL.

Following the results of our Julia/JuMP prototype on Trial Event 1, we decided to move our development over to C++, in order to speed-up evaluation of derivatives within the interior-point method driving Ipopt and take advantage of more advanced (primal-dual) warm-starting capabilities only accessible from lower-level Ipopt interfaces. Our approach in C++ was initially the same as in the Julia/JuMP prototype, but we later developed a crashing and projection approach for AGC and PV/PQ complementarity constraints in the contingencies. This was followed up by efficient hot-starting techniques rooted deeply in the theory of interior-point methods to allow fast re-optimization of the crashing and projection problems. This enabled a very effective numerical solution approach for the post-contingency and allowed us to solve the largest cases present in Trial Event 1 and Trial Event 2 with high levels of accuracy.

Accordingly, after Trial Event 2 we moved towards a surrogate optimization approach, where we would solve the base case augmented by convex penalty objective terms for the outage components (*e.g.*, penalizing the apparent flow on a line failing in a contingency). The formula for the penalty terms was eventually based on quartic polynomials following empirical evidence that they were effectively preventing inaccurately large base case (re)action to impactful contingencies. At this stage, a large portion of our effort was dedicated to implement an asynchronous parallel schedule algorithm that resolves base case and post-contingency subproblems simultaneously to make better use of the (limited) computational cores. The algorithm was first deployed in Trial Event 3 and later the implementation was refined to use non-blocking interprocess communication.

Finally, between Trial Event 3 and the Final Event of Challenge 1 we focused our efforts into testing and tuning our C++ implementation. As part of this effort, we modified the Ipopt code to address a couple of rare freezes and refined the contingency evaluation code to return feasible solutions increasingly quicker when the strict execution time limitation of the competition appeared to be violated. In this phase we had assembled for and used in the testing instances more than twice as large than those included in the trial events.

1.3 Project Outputs

a. Journal Articles

- Cosmin G. Petra, Ignacio Aravena (2023) A Surrogate-Based Asynchronous Decomposition Technique for Realistic Security-Constrained Optimal Power Flow Problems. Operations Research. URL: `https://doi.org/10.1287/opre.2022.0229`.
- Ignacio Aravena, Daniel K. Molzahn, Shixuan Zhang, Cosmin G. Petra, Frank E. Curtis, Shenyinying Tu, Andreas Wächter, Ermin Wei, Elizabeth Wong, Amin Gholami, Kaizhao Sun, Xu Andy Sun, Stephen T. Elbert, Jesse T. Holzer, Arun Veeramany (2023) Recent Developments in Security-Constrained AC Optimal Power Flow: Overview of Challenge 1 in the ARPA-E Grid Optimization Competition. Operations Research. URL: `https://doi.org/10.1287/opre.2022.0315`.

b. Websites Featuring Project Work Results

- ARPA-E GOC Challenge 1 dedicated congratulations website: `https://gocompetition.energy.gov/kudos-livermore`
- LLNL News article: `https://www.llnl.gov/news/lab-team-sizzles-doe-grid-optimization-competition`
- ARPA-E GOC Challenge 1 leaderboards Trial Event 1: `https://gocompetition.energy.gov/challenges/challenge-1/leaderboards-trial-event-1`
- ARPA-E GOC Challenge 1 leaderboards Trial Event 2: `https://gocompetition.energy.gov/challenges/challenge-1/leaderboards-trial-event-2`
- ARPA-E GOC Challenge 1 leaderboards Trial Event 3: `https://gocompetition.energy.gov/challenges/challenge-1/leaderboards-trial-event-3`
- ARPA-E GOC Challenge 1 leaderboards Final Event: `https://gocompetition.energy.gov/challenges/challenge-1/leaderboards-final-event`

c. Awards, Prizes, and Recognition
Lawrence Livermore National Laboratory, Global Security, Gold Award, 2020.

1.4 Follow-On Funding

Presented in Table 1.2.

Table 1.2: Follow-On Funding Received.

Source	Funds Committed or Received
US DOE ARPA-E	Prize follow-on award: $400,000

Chapter 2

ARPA-E GO Competition Challenge 2 – magos team

2.1 Accomplishments and Objectives

This award allowed the LLNL-lead team *magos* to develop a state-of-the-art approach for the next-snapshot formulation of the security-constrained alternating-current optimal power flow problem (NS-SCACOPF) put forward by the ARPA-E GOC Challenge 2 organization team [6]. The *magos* approach consists of an ADMM-based decomposition using relying on nonlinear optimization, rounding heuristics, and power flow approximations. This approach was among the average performance throughout trial events in Challenge 2, but underperformed in the Final Event.

A number of tasks and milestones were laid out in Attachment 1, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized in Table 2.1.

Table 2.1: Key Milestones and Deliverables

Tasks	Milestones and Deliverables
Task 1: Registration	Register for Challenge 2 of the GO Competition on the competition website (https://gocompetition.energy.gov/) **Actual Performance:** (September 20, 2020) Registration of all team members completed and approved by ARPA-E.
Task 2: Commercialization Plan	Commercialization Plan submitted to and approved by ARPA-E GO Competition Administrator. **Actual Performance:** (August 4, 2021) Submitted initial valid approach to Sandbox.
Task 3: Trial 1 Event	Participate in the Trial 1 Event of Challenge 2; results must be displayed on the leaderboards. **Actual Performance:** (December 4, 2020) Approach for Trial 1 Event submitted before deadline. Trial 1 leaderboards made public by ARPA-E on January 8, 2021.
Task 4: Trial 2 Event	Participate in the Trial 2 Event of Challenge 2; results must be displayed on the leaderboards. **Actual Performance:** (May 4, 2021) Approach for Trial 2 Event submitted before deadline. Trial 1 leaderboards made public by ARPA-E on May 21, 2021.
Task 5: Final Event	Participate in the Challenge 2 Final Event; results must be displayed on the leaderboards. Certification to ARPA-E that the project has been completed. **Actual Performance:** (August 12, 2021) Approach for Final Event submitted before deadline. Certification of results completed by September 20, 2021. Final Event leaderboards made public by ARPA-E on October 4, 2021.

2.2 Project Activities

The NS-SCACOPF formulation for ARPA-E GOC Challenge 2 [6] accounted for nonlinear alternating current power flow equations for both the base case and post-contingency states. It modeled transmission lines; transformers and phase shifters with variable (discrete) tap settings; shunts with discrete tap settings; flexible consumers; and generators with ramp rate limits between base case and post-contingencies. Transmission lines, transformers, and phase shifters could be open or closed at will (a setting known as *optimal transmission switching*), and generators can be set on or off (*unit commitment*). Transitions between base case and post-contingency states were only limited by ramp-rate constraints of generators. The most complicating aspects in this NS-SCACOPF formulation are the size of the problem and the presence of both nonlinearity and discrete decision variables.

The *magos* team deviced a solution approach based on decomposing the problem into base case, post-contingency states, and a coordination subproblem, iterating among them using the alternating direction method of multipliers (ADMM). The base case problem was solved in a 3-step approach: first solving the (nonlinear) continuous relaxation, then rounding discrete decisions, and then re-solving with fix discrete decisions. Post-contingency subproblems were solved using approximations, first a DC approximation, and later an active-only approximation with voltage constraints. The coordination subproblem was a mixed-integer (convex) quadratic problem, solved directly using branch-and-bound algorithm. The approach was initially implemented using Julia/JuMP to formulate subproblems, Ipopt compiled with Intel MKL and HSL to solve nonlinear problems, and Gurobi to mixed-integer quadratic problems. Following results in Trial Event 1 and Trial Event 2, the team ported the base case solution approach to C++, in order to speed-up iterations. The Final Event implementation combined then C++ functions called from Julia, with native Julia/JuMP code and calls to solver libraries Ipopt and Gurobi.

2.3 Project Outputs

a. Conference Presentations
   Nai-Yuan Chiang, Ignacio Aravena, and Quentin Lété, "Asynchronous Decomposition for SCACOPF with Discrete Decision Variables," INFORMS 2020.

b. Networks/Collaborations Fostered
   Leveraged experience in Challenge 1 and Challenge 2 to partner with ECCO International, Inc. for ARPA-E GOC Challenge 3 FOA.

c. Websites Featuring Project Work Results

   - ARPA-E GOC Challenge 1 leaderboards Trial Event 1: `https://gocompetition.energy.gov/challenges/challenge-2/Leaderboards/Trial1`
   - ARPA-E GOC Challenge 1 leaderboards Trial Event 2: `https://gocompetition.energy.gov/challenges/challenge-2/Leaderboards/Trial2`

- ARPA-E GOC Challenge 1 leaderboards Trial Event 3: `https://gocompetition.energy.gov/challenges/challenge-2/Leaderboards/Trial3`
- ARPA-E GOC Challenge 1 leaderboards Final Event: `https://gocompetition.energy.gov/challenges/challenge-2/Leaderboards/Final`

2.4 Follow-On Funding

Presented in Table 2.2.

Table 2.2: Follow-On Funding Received.

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

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