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Title: ARPA-e Grid Optimization Competition: Benchmark Algorithm Overview

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ARPA-e Grid Optimization Competition

Benchmark Algorithm Overview



Carleton Coffrin
Advanced Network Science Initiative
<https://lanl-ansi.github.io/>

My Role in the Competition

- **Develop the ARPA-e Benchmark Algorithm**
 - Early test driving of the platform and datasets
 - Develop and test various solution approaches
- **Release the Benchmark Algorithm
(PowerModelsSecurityConstrained)**
 - An open-source platform for R&D on SCOPF algorithms
 - <https://github.com/lanl-ansi/PowerModelsSecurityConstrained.jl>
- **Instance Analysis**
 - Search for unexpected issues in datasets
 - Estimating problem difficulty (e.g. optimality gaps)

What is the competition problem?

Why is it challenging?

Competition Problem Specification Document

- <https://gocompetition.energy.gov/challenges/challenge-2/formulation>
- 97 Pages (mathematical program 9-31)
- I will focus on key intuitions
 - Skip the details



Grid Optimization Competition Challenge 2 Problem Formulation

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Arun Veeramany Jessica Wert

May 31, 2021

1 Introduction

1.1 Background

This document contains the official formulation that will be used for evaluation in Challenge 2 of the Grid Optimization (GO) Competition. Minor changes may occur within the formulation. Entrants will be notified when a new version is released. Changes are not expected to be of a significance that would cause a change in approach for the Entrants.

This formulation builds upon the Challenge 1 formulation published in ARPA-E DE-FOA-0001952. Entrants will be judged based on the current official Challenge 2 formulation posted on the GO Competition website (this document, which is subject to change), not the formulation posted in DE-FOA-0001952. Entrants are permitted and encouraged to use any alternative problem formulation and modeling convention within their own software (such as convex relaxation, decoupled power flow formulations, current-voltage formulations, etc.) in an attempt to produce an exact or approximate solution to this particular mathematical program. However, the judging of all submitted approaches must conform to the official formulation presented here.

The following mathematical programming problem is a type of a security-constrained (AC based) optimal power flow, or SCOPF. There are many ways to formulate the SCOPF problem; this document may present multiple equivalent options for specified constraints. Entrants are strongly encouraged to study this formulation precisely and to engage with the broader community if anything is not clear (please see the FAQs and forum on the GO Competition website, <https://gocompetition.energy.gov/>).

This SCOPF problem is defined to be an alternating current (AC) formulation, which is based on a bus-branch power system network model with security constraints. In general, Entrants are tasked with determining the optimal dispatch and control settings for power generation and grid control equipment in order to maximize the market surplus associated with the operation of the grid, subject to pre- and post-contingency constraints. Feasible solutions must conform to operating standards including, but not limited to: minimum and



Some Key Problem Features

- Optimal Power Flow “like” problem
- Full AC Steady-State Physics
 - Similar to commercial operational tools (PSSE, PowerWorld)
 - N-1 Security Constraints
- Co-Optimization of Generation and Load Dispatch
 - Price responsive demand
- Unit Commitment
 - Including ramping requirements
- Topology Optimization
 - Add/remove branches from service
- And more ...



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Competition Problem Complexity and Instance Size

- **Problem Class Non-Convex MINLP**
 - Non-convex nonlinear equations
 - Discrete variables (component participation, control settings)
- **Competition network sizes**
 - Up to 31,000 nodes / 40,000 edges / 5,000 contingencies
- **Writing down the mathematical program as described**
 - 900,000,000 continuous decision variables
 - 250,000,000 discrete decision variables
 - comparable number of constraints

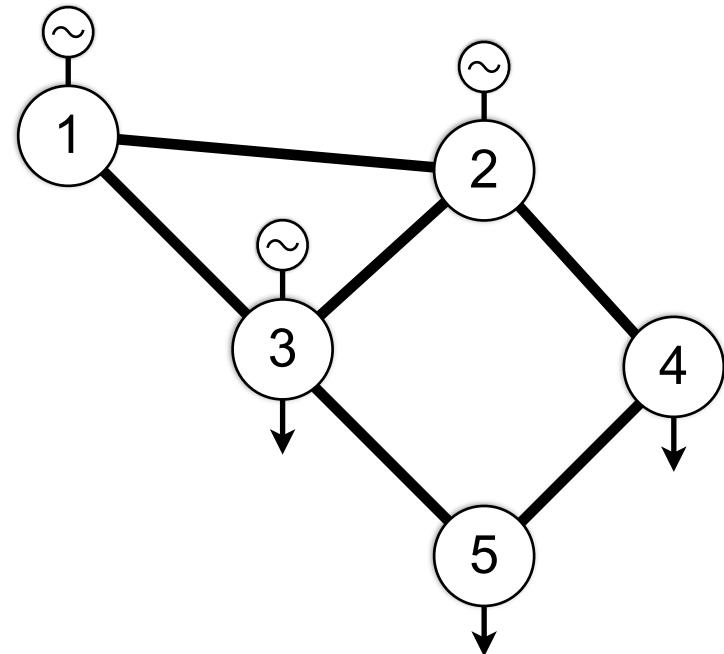
AND solve in
< 5 minutes
< 60 minutes

What is the completion problem?

Start with **Optimal Power Flow**
as a building block

What is Optimal Power Flow?

- A natural and fundamental transmission network optimization problem
 - Instantious economic dispatch of the grid
- Given
 - A Power Transmission Network
 - Required Demands (i.e. customer loads)
 - Generator Cost Functions
- Minimize
 - The cost of generating power
- Subject To
 - Meeting the required demands
 - Network and generator operation constraints



Physics of power networks leads to non-convex nonlinear problem!

A Conical OPF Formulation [1]

variables:

$$S_i^g \quad \forall i \in G$$

$$V_i \quad \forall i \in N$$

minimize:

$$\sum_{i \in G} f(S_i^g) \quad \leftarrow$$

Minimize Generation Cost (convex)
(or Maximize Market Value)

subject to:

$$(\mathbf{v}_i^l)^2 \leq V_i V_i^* \leq (\mathbf{v}_i^u)^2 \quad \forall i \in N$$

$$S_i^{gl} \leq S_i^g \leq S_i^{gu} \quad \forall i \in G$$

$$\sum_{k \in G_i} S_k^g - S_i^d = \sum_{(i,j) \in E_i \cup E_i^R} S_{ij} \quad \forall i \in N$$

$$S_{ij} = \mathbf{Y}_{ij}^* V_i V_i^* - \mathbf{Y}_{ij}^* V_i V_j^* \quad (i, j) \in E \cup E^R$$

$$|S_{ij}|^2 \leq (\mathbf{s}_{ij}^u)^2 \quad \forall (i, j) \in E \cup E^R$$

[1] Coffrin, Carleton, Hassan L. Hijazi, and Pascal Van Hentenryck. "The QC relaxation: A theoretical and computational study on optimal power flow." IEEE Transactions on Power Systems 31.4 (2015): 3008-3018.

Large-Scale Non-Convex NLP!

Solution Approaches and Scalability

- **Interior Point Algorithms (e.g. Ipopt, KNITRO)**
 - Second-order gradient decent like approaches
 - Only provide locally optimality, but seems to be very near globally optimal in practice
- **Sequential Linear/Quadratic Programming (e.g. gurobi, cplex)**
 - Linearized around an operating point; Optimize; Repeat
 - Only provide locally optimality, but seems to be sufficient in practice
- **Problem Scales**
 - 30,000 node network in 300 seconds
 - Cases curated here, <https://github.com/power-grid-lib/pglib-opf>

What is the completion problem?

Beyond Optimal Power Flow

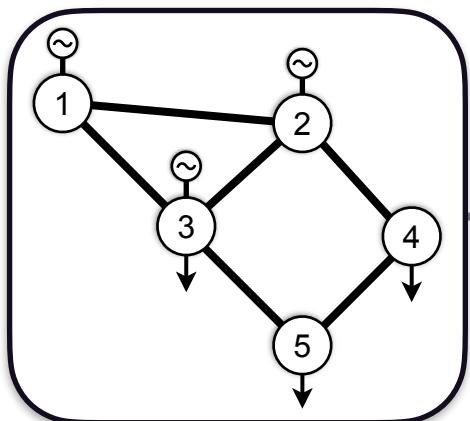
Balance Cost and Resilience

- **Power Networks are regulated to be “N-1 Secure”**
 - Intention, the network can withstand the spontaneous failure of any single component during daily operations
- **Lots of details in practice**
 - Focus on a specific subset of component failures
 - Many constraints can be exceeded for a short amount of time
 - What time scale? (e.g. seconds vs minutes)
 - Available recourse actions?

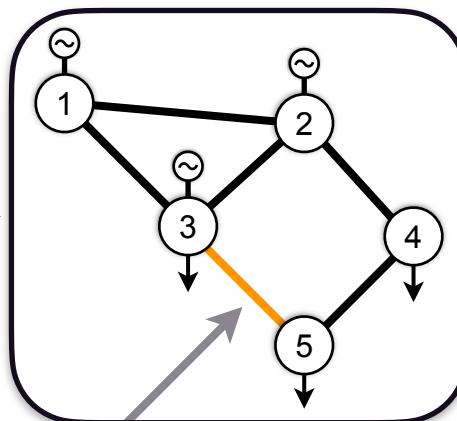


Competition OPF with Security Constraints

Pervious Operating Point (fixed)

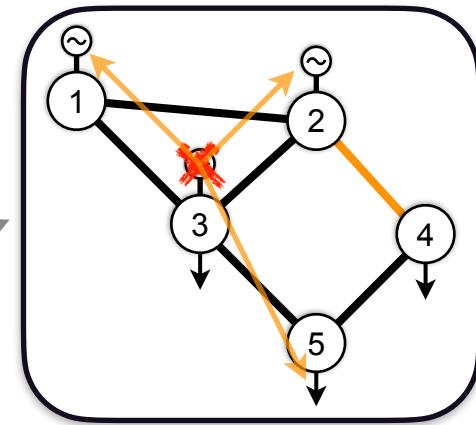


Cost Minimal OPF Solution

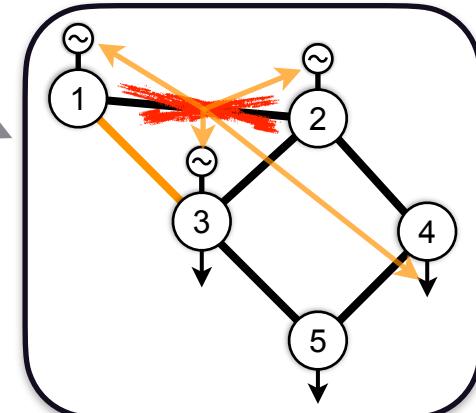


Binding Flow Limit

Generation Lost



Line Lost



...

Competition Objective Function (simplified)

- Recall the OPF Objective

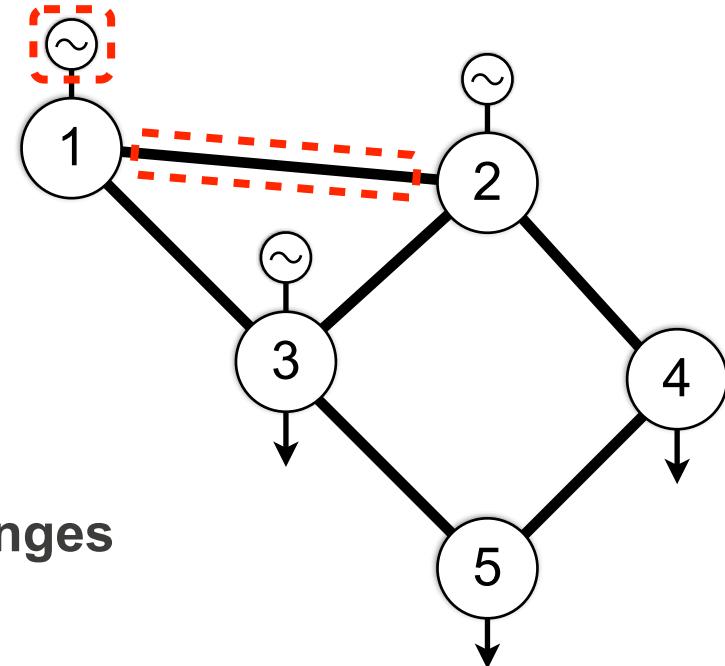
$$\sum_{i \in G} f(S_i^g)$$

- Competition Objective

$$\sum_{i \in G} f(S_i^g) + 1/|C| \sum_{c \in C} \left(\sum_{i \in G} f(S_{ci}^g) \right)$$

Discrete Decision Variables

- Occur in first-stage and all contingency stages
- Unit Commitment: $\{0,1\}$
- Transmission Switching: $\{0,1\}$
 - a network design problem!
- Transformer Taps: $\{-20, -19, \dots, 19, 20\}$
 - with impedance correction tables
- Bus Shunts: a variety of small integer ranges



How to approach competition problem?

Competition Problem, Core Insights

- **Heuristics are essential**
 - Lots of testing one feature at a time to find the best bang-for-the-buck
- **It seems safe to ignore the impacts of the contingency stage**
 - Objective penalties are small compared to cost savings in the first-stage
 - Easy to recovery from loss of components with second-stage re-dispatch
- **Solve an OPF in second-stage (i.e. code2)**
 - Keep discrete variables fixed (mitigate problem the complexity)
 - Important to take advantage of extra “ramping” time

Competition Problem, Core Insights

- **How to treat the discrete parameters?**
 - Carefully tuned rounding heuristics
- **Pose the full non-convex MINLP problem (with discrete variables)**
 - Relax the discrete variables to a continuous range
 - Solve relaxed non-convex NLP problem
 - Round discrete variables that are “close” to an integer value (0,1)
 - Resolve rounded non-convex NLP problem
- **Most important discrete variables**
 - Unit Commitment is the most valuable (solve first)
 - Topology control is less valuable and also impacted by UC (solve second)
 - Phase shifting transformers (TBD)

Competition Problem, Additional Problem Simplifications

- Solve simple OPF in second-stage (keep discrete variables fixed)
- Skip optimization of transformers (set by a simple heuristic)
- Skip optimization of shunts (leave at initial value)
- Simplify penalty functions (linear approximation)
- Clean the data! (basic pre-solver)
 - Improve variable bounds
 - Remove values that are not possible
 - Increase costs associated with discrete variable controls

ARPA-e Benchmark Algorithm

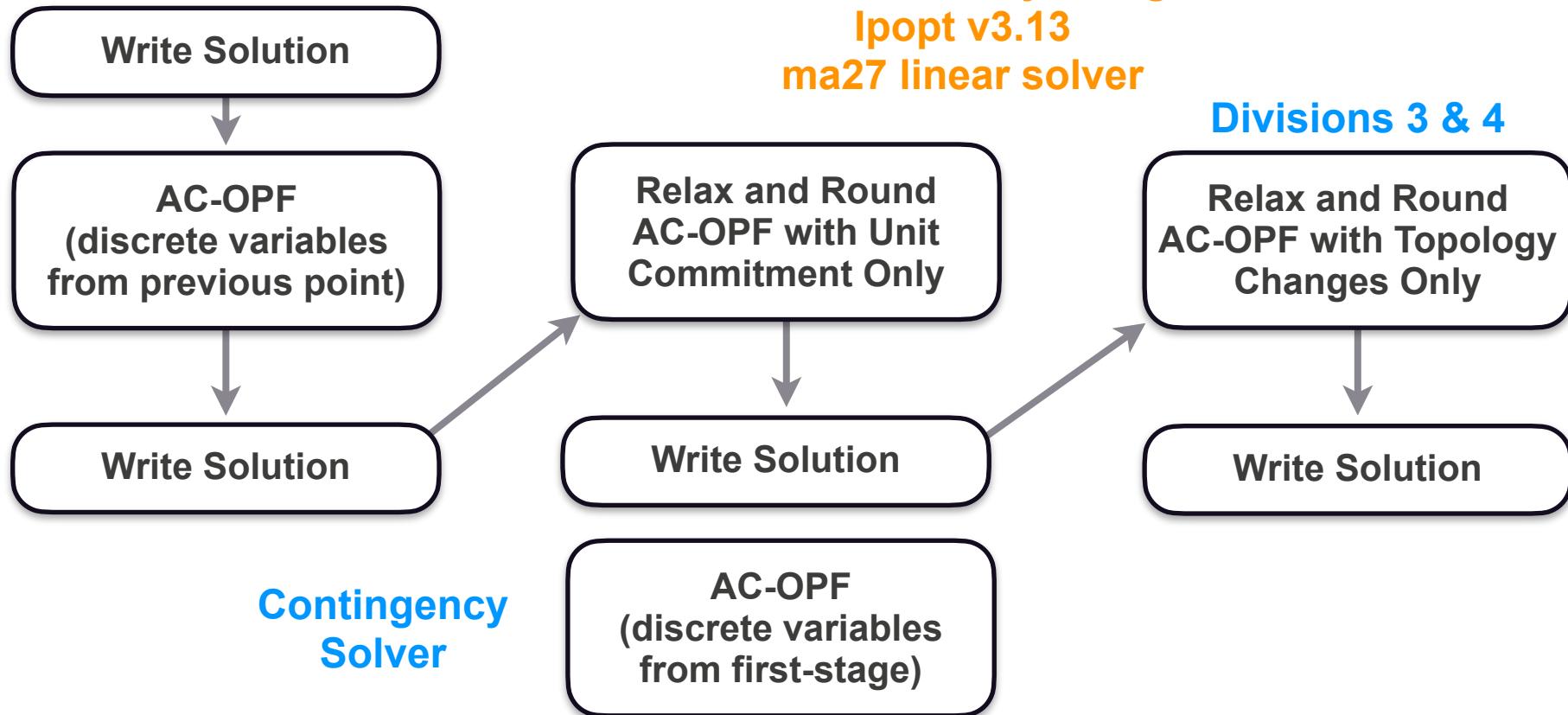
- **Solver reliability is essential!**

AC-OPF heavy lifting

Ipopt v3.13

ma27 linear solver

Divisions 3 & 4

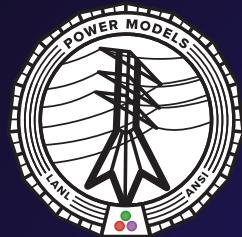


ARPA-e Benchmark Algorithm

- **Trial 3 Datasets**
 - 81 networks ranging from 600 to 31000 buses
- **AC-OPF in Base Case Only**
 - Typical objective improvement 70%
- **Additional UC Improvement**
 - Improves 75% of cases
 - Typical objective improvement 43%
- **Additional OTS Improvement**
 - Improves 20% of cases
 - Typical objective improvement 1%

ARPA-e Benchmark Algorithm

- **Focus on finding the best-possible solutions (not performance)**
- **Solves 3-5 OPF-like problems to find the base-case operating point**
 - Significant engineering is required to speed up this core AC-OPF
 - Parallel derivative computations, improve cacheing of pre-compiled Julia code
- **Notable performance degradation under aggressive time limits**
 - Divisions 1 & 3 - 5 minute time limit
 - First AC-OPF fails to converge on largest network cases
 - Divisions 2 & 4 - 60 minute time limit
 - Usually all stages complete



PowerModelsSecurityConstrained

The ARPA-e Benchmark Algorithm Source Code

<https://github.com/lanl-ansi/PowerModelsSecurityConstrained.jl>

The screenshot shows the GitHub repository page for `lanl-ansi / PowerModelsSecurityConstrained.jl`. The page has a dark theme. At the top, there is a navigation bar with a search bar, a pull requests button, an issues button, a marketplace button, an explore button, and a user profile icon. Below the navigation bar, the repository name is displayed in a blue header. To the right of the repository name are buttons for 'Unwatch' (with a count of 1), 'Star' (with a count of 2), 'Fork' (with a count of 0), and a dropdown menu. Below the header, there is a navigation bar with tabs for 'Code' (which is selected), 'Issues' (6), 'Pull requests' (0), 'Actions', 'Security', 'Insights', and 'Settings'. A summary section below the navigation bar shows '37 commits', '6 branches', '0 packages', '2 releases', '1 environment', '1 contributor', and a 'View license' button. At the bottom of the page, there are buttons for 'Branch: master', 'New pull request', 'Create new file', 'Upload files', 'Find file', and 'Clone or download'. A footer at the very bottom shows a commit message from 'ccoffrin' and a note about the latest commit.

A PowerModels Extension for Security Constrained Optimization Problems <https://lanl-ansi.github.io/PowerMode...>

Manage topics

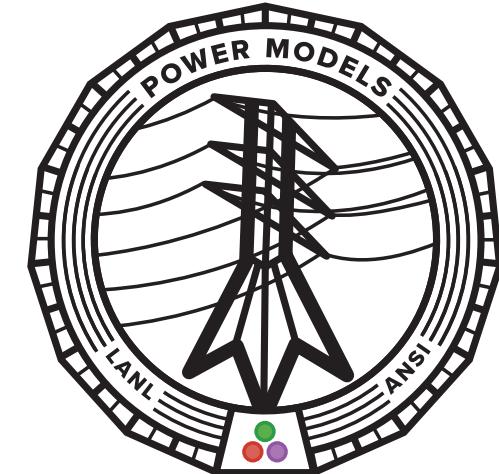
37 commits 6 branches 0 packages 2 releases 1 environment 1 contributor View license

Branch: master New pull request Create new file Upload files Find file Clone or download

ccoffrin add tagbot github action ✓ Latest commit a032fe1 yesterday

Conclusions

- **Challenge 2, keys to success**
 - Recognize AC-OPF is “good enough”
 - Focus computing efforts on the most valuable decision variables
- **Notable Success of Julia and JuMP**
 - As easy as Matlab, high performance, free and open-source
- **PowerModelsSecurityConstrained**
 - Ripe testbed for R&D



Thanks!