Solving the Grid Optimization Competition Challenge 3 Problem

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Bernard Knueven

Mixed Integer Programming Workshop 2024

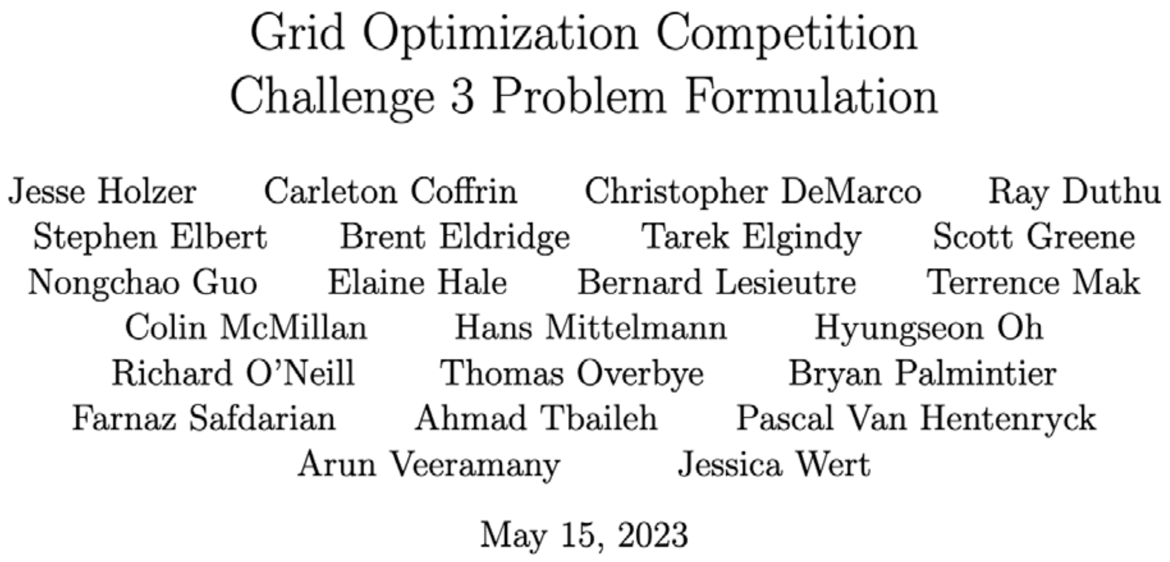
5 June 2024

Problem Statement

Problem Statement

- Multiperiod security constrained AC unit commitment
  - Nonlinear AC power flow / balance
    - Real/reactive power production/consumption and balance
    - Voltage magnitude/angle
    - Discrete shunt steps
    - Topology optimization
  - Branch contingencies using linear real power flow / balance
  - Detailed generator/load modeling
    - Startup/shutdown
    - Reactive power limits determined by real power output
    - Minimum up/down requirements
  - Suite of reserve products (both generators and loads)
- Objective: Find the best solution

Problem Statement



Grid Optimization Competition
Challenge 3 Problem Formulation

Jesse Holzer Carleton Coffrin Christopher DeMarco Ray Duthu
Stephen Elbert Brent Eldridge Tarek Elgindy Scott Greene
Nongchao Guo Elaine Hale Bernard Lesieutre Terrence Mak
Colin McMillan Hans Mittelmann Hyungseon Oh
Richard O'Neill Thomas Overbye Bryan Palmintier
Farnaz Safdarian Ahmad Tbaileh Pascal Van Hentenryck
Arun Veeramany Jessica Wert

May 15, 2023

https://gocompetition.energy.gov/sites/default/files/Challenge3_Problem_Formulation_20230515.pdf

- 62 pages
- 320 equations
- ~400 pieces of nomenclature

- Solution evaluation code provided by PNNL

Competition Format

- Four Events
  - January 2023
  - April 2023
  - June 2023 (Prize Money)
  - September 2023 (Prize Money)
- Code is submitted to Pacific Northwest National Laboratory (PNNL) and evaluated using a single node on their cluster
  - 64-cores (2 AMD EPYC 7502 CPUs)
  - 256 GB memory
  - Linux (Centos 7.8)

Technical Details

Created On: 09/01/2023 - 16:44

Repository Name: KnOWS

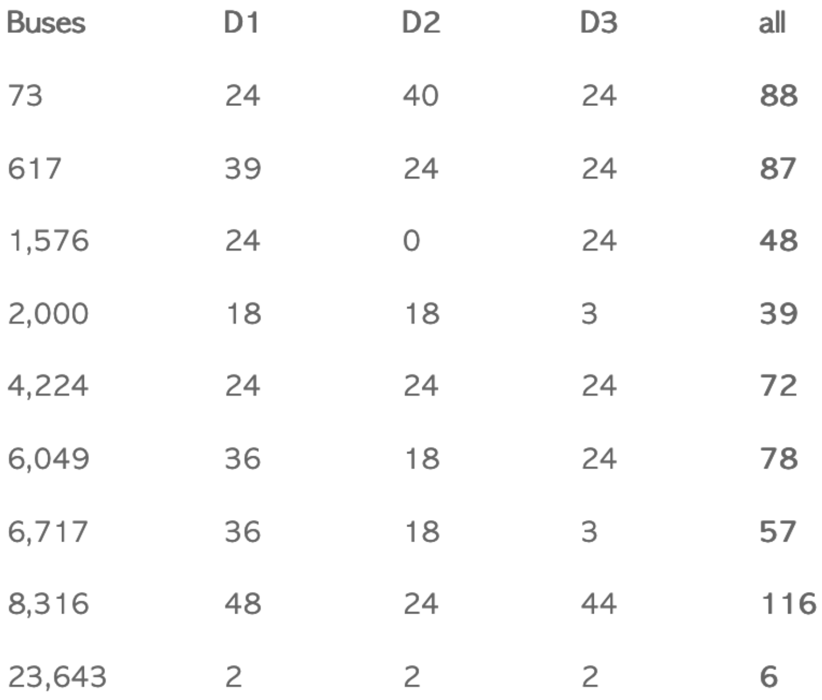
Repository Branch: deployment

Configuration Information from submission.conf:

```
dataset=E3.1
model=C3E3N00617D1
scenario=001
language=cpp

export GUROBI_HOME=$GUROBI_1002_HOME
export PATH="$GUROBI_HOME/bin:$PATH”
export GRB_LICENSE_FILE="$APPS_BASE/gurobi/license/gurobi_client.lic”

export LD_LIBRARY_PATH="$GUROBI_HOME/lib:$LD_LIBRARY_PATH”
export LD_LIBRARY_PATH="$OUTPUT_DIR/../src/lib:$LD_LIBRARY_PATH”
export LD_LIBRARY_PATH="$APPS_BASE/ipopt_dependencies/usr/local
/lib:$LD_LIBRARY_PATH”

module load mkl cmake gcc/11.2.0 mvapich2/2.3.7 boost/1.68
srun_options=-n 48
```

Problem Instances

- Three Divisions
  - Real Time Unit Commitment (D1)
    - 10-minute time limit
    - 18 time-periods
  - Day-Ahead Unit Commitment (D2)
    - 120-minute time limit
    - 48 time-periods
  - Week-Ahead Unit Commitment (D3)
    - 240-minute time limit
    - 44 time-periods



Buses	D1	D2	D3	all
73	24	40	24	88
617	39	24	24	87
1,576	24	0	24	48
2,000	18	18	3	39
4,224	24	24	24	72
6,049	36	18	24	78
6,717	36	18	3	57
8,316	48	24	44	116
23,643	2	2	2	6

Solution Approach

Competition Team (The Blackouts)

- University of Tennessee
  - Jim Ostrowski
  - Ethan Deakins
- Lawrence Livermore National Laboratory
  - Jean-Paul Watson
  - Jonathan Schrock
- Sandia National Laboratories
  - Bill Hart

Solution Approach

- Multiperiod security constrained AC unit commitment
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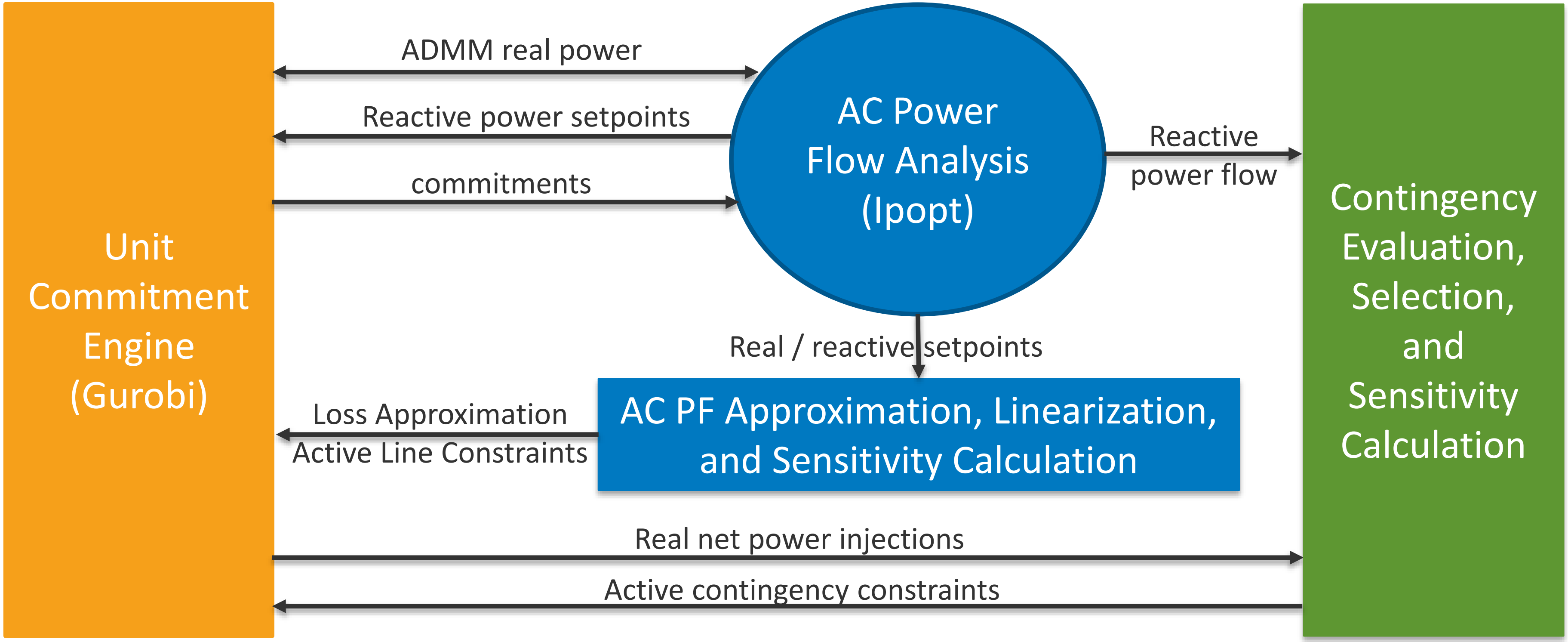
NLP / Ipopt

Custom
Lazy
Evaluation

MIP / Gurobi

Solution Approach



Unit Commitment Engine (Gurobi)

ADMM real power

Reactive power setpoints

commitments

AC Power Flow Analysis (Ipopt)

Reactive power flow

Contingency Evaluation, Selection, and Sensitivity Calculation

Real / reactive setpoints

AC PF Approximation, Linearization, and Sensitivity Calculation

Loss Approximation

Active Line Constraints

Real net power injections

Active contingency constraints

Software Stack

- Implemented in C++
- Gurobi 10
- Coek modeling library
- Ipopt
  - HSL MA97
  - AMPL ASL
- UMFPACK
- Eigen
- MPI

AC Power Flow

AC Power Flow / Balance

$$\min \sum_{c \in C} \left(-w_c p_c + \rho/2 \left(p_c - \widehat{p_c}^{UC} \right)^2 \right) + \sum_{g \in G} \left(-w_g p_g + \rho/2 \left(p_g - \widehat{p_g}^{UC} \right)^2 \right)$$

$$\sum_{c \in C_i} p_c + \sum_{l \in L_i^{fr}} p_l^{\mathrm{fr}} + \sum_{l \in L_i^{to}} p_l^{\mathrm{to}} = \sum_{g \in G_i} p_g \qquad \forall i$$

$$\sum_{c \in C_i} q_c + \sum_{l \in L_i^{fr}} q_l^{\mathrm{fr}} + \sum_{l \in L_i^{to}} q_l^{\mathrm{to}} = \sum_{g \in G_i} q_g \qquad \forall i$$

$$p_l^{\mathrm{fr}} = G_l v_{i(l)}^2 - G_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{i(j)}\right) - B_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right) \qquad \forall l$$

$$p_l^{\mathrm{to}} = G_l v_{j(l)}^2 - G_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{i(j)}\right) + B_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right) \qquad \forall l$$

$$q_l^{\mathrm{fr}} = -B_l v_{i(l)}^2 + B_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{i(j)}\right) - G_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right) \qquad \forall l$$

$$q_l^{\mathrm{to}} = -B_l v_{j(l)}^2 + B_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{i(j)}\right) + G_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right) \qquad \forall l$$

$$v_i^{\min} \le v_i \le v_i^{\max} \qquad \forall i$$

commitments from UC

Unit Commitment: Transmission Limits & ADDM

$$\min \quad -z^{\mathrm{ms}} + \sum_{c \in C} \left(w_c p_c + \rho/2 \left(p_c - \widehat{p_c}^{AC}\right)^2 \right) + \sum_{g \in G} \left(w_g p_g + \rho/2 \left(p_g - \widehat{p_g}^{AC}\right)^2 \right)$$

$$+ \sum_{c \in C} \left(\rho/2 \left(q_c - \widehat{q_c}^{AC}\right)^2 \right) + \sum_{g \in G} \left(\rho/2 \left(q_g - \widehat{q_g}^{AC}\right)^2 \right)$$

subject to:

$$\sum_{c \in C} p_c + p^{\mathrm{loss}} = \sum_{g \in G} p_g$$

hundreds more constraints…

Questions: What to do about loss term p^{loss}? Transmission Limits?

Transmission Limits

$$\left(\left(p_l^{\mathrm{fr}}\right)^2 + \left(q_l^{\mathrm{fr}}\right)^2\right)^{1/2} \leq s_l^{\max} + s_l^+ \qquad \forall l$$

$$\left((p_l^{\mathrm{to}})^2 + (q_l^{\mathrm{to}})^2\right)^{1/2} \leq s_l^{\max} + s_l^+ \qquad \forall l$$

- s_l^+ is a nonnegative slack variable which allows for violation of transmission constraints
- Loads are completely relaxed as dispatchable
  - Violating transmission constraints could be optimal!
- Delegate ALL economic tradeoffs to the unit commitment problem
- Approximate AC line flows, then linearize

Approximating Flow

- Approximate: Midline flow (Garcia et al. 2019)

$$\begin{array}{rl} 0.5 & p_l^{\text{fr}} = G_l v_{i(l)}^2 - G_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{i(j)}\right) - B_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right) \\ -0.5 & p_l^{\text{to}} = G_l v_{j(l)}^2 - G_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{i(j)}\right) + B_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right) \\ \hline \end{array}$$

$$p_l^{\text{fr,avg}} = G_l\left(v_{i(l)}^2 - v_{j(l)}^2\right)/2 - B_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right)$$

- Linearize w.r.t θ:

$$\begin{aligned} \tilde{p}_l^{\text{fr,avg}} &= G_l\left(\hat{v}_{i(l)}^2 - \hat{v}_{j(l)}^2\right)/2 - B_l \hat{v}_{i(l)} \hat{v}_{j(l)} \sin\left(\hat{\theta}_{i(l)} - \hat{\theta}_{j(l)}\right) \\ &\quad - B_l \hat{v}_{i(l)} \hat{v}_{j(l)} \cos\left(\hat{\theta}_{i(l)} - \hat{\theta}_{j(l)}\right)\left(\theta_{i(l)} - \theta_{j(l)}\right) \end{aligned}$$

Approximating Loss

- Calculate Loss:

$$\begin{array}{rl} & p_l^{\text{fr}} = G_l v_{i(l)}^2 - G_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{i(j)}\right) - B_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right) \\ + & p_l^{\text{to}} = G_l v_{j(l)}^2 - G_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{i(j)}\right) + B_l v_{i(l)} v_{j(l)} \sin\left(\theta_{i(l)} - \theta_{j(l)}\right) \\ \hline & p_l^{\text{loss}} = G_l\left(v_{i(l)}^2 + v_{j(l)}^2\right) - 2G_l v_{i(l)} v_{j(l)} \cos\left(\theta_{i(l)} - \theta_{j(l)}\right) \end{array}$$

- Linearize w.r.t θ:

$$\begin{aligned} \tilde{p}_l^{\text{loss}} = G_l\left(\hat{v}_{i(l)}^2 - \hat{v}_{j(l)}^2\right) - 2G_l \hat{v}_{i(l)} \hat{v}_{j(l)} \cos\left(\hat{\theta}_{i(l)} - \hat{\theta}_{j(l)}\right) \\ +2_l \hat{v}_{i(l)} \hat{v}_{j(l)} \sin\left(\hat{\theta}_{i(l)} - \hat{\theta}_{j(l)}\right)\left(\theta_{i(l)} - \theta_{j(l)}\right) \end{aligned}$$

- Summary:

$$p_l^{\text{fr}} \approx \tilde{p}_l^{\text{fr,avg}} + 0.5\tilde{p}_l^{\text{loss}}$$

$$p_l^{\text{to}} \approx -\tilde{p}_l^{\text{fr,avg}} + 0.5\tilde{p}_l^{\text{loss}}$$

Power Balance

- Bus power balance:

$$\sum_{c\in C_i} p_c + \sum_{l\in L_i^{fr}} \left(\tilde{p}_l^{\text{fr,avg}} + 0.5\tilde{p}_l^{\text{loss}}\right) - \sum_{l\in L_i^{to}} \left(\tilde{p}_l^{\text{fr,avg}} - 0.5\tilde{p}_l^{\text{loss}}\right) = \sum_{g\in G_i} p_g \quad \forall i$$

- Sum across all buses i:

$$\sum_{c\in C} p_c + \underbrace{\sum_{l\in L} \tilde{p}_l^{\text{loss}}}_{p^{\text{loss}}} = \sum_{g\in G} p_g$$

- Project out θ (lots of linear algebra):

$$\tilde{p}_l^{\text{fr,avg}} = \alpha_l^0 + \sum_{c\in C} \alpha_l^c p_c + \sum_{g\in G} \alpha_l^g p_g \qquad p^{\text{loss}} = \alpha_{\text{loss}} + \sum_{c\in C} \alpha_{\text{loss}}^c p_c + \sum_{g\in G} \alpha_{\text{loss}}^g p_g$$

Transmission Limits

$$\left(\left(p_l^{\text{fr}}\right)^2 + \left(q_l^{\text{fr}}\right)^2\right)^{1/2} \leq s_l^{\max} + s_l^{+} \qquad \forall l$$

$$\left((p_l^{\text{to}})^2 + (q_l^{\text{to}})^2\right)^{1/2} \leq s_l^{\max} + s_l^{+} \qquad \forall l$$

To incorporate in UC:

1. Replace p_l^{fr} / p_l^{to} with their approximation $\tilde{p}_l^{\text{fr,avg}}$ / $-\tilde{p}_l^{\text{fr,avg}}$
2. Use $\hat{q}_l^{\text{fr}}$ / $\hat{q}_l^{\text{to}}$ from AC base point
3. Linearize around $\hat{p}_l^{\text{fr}}$ / $\hat{p}_l^{\text{to}}$ / $\hat{s}_l^{+}$ calculated from AC base point:

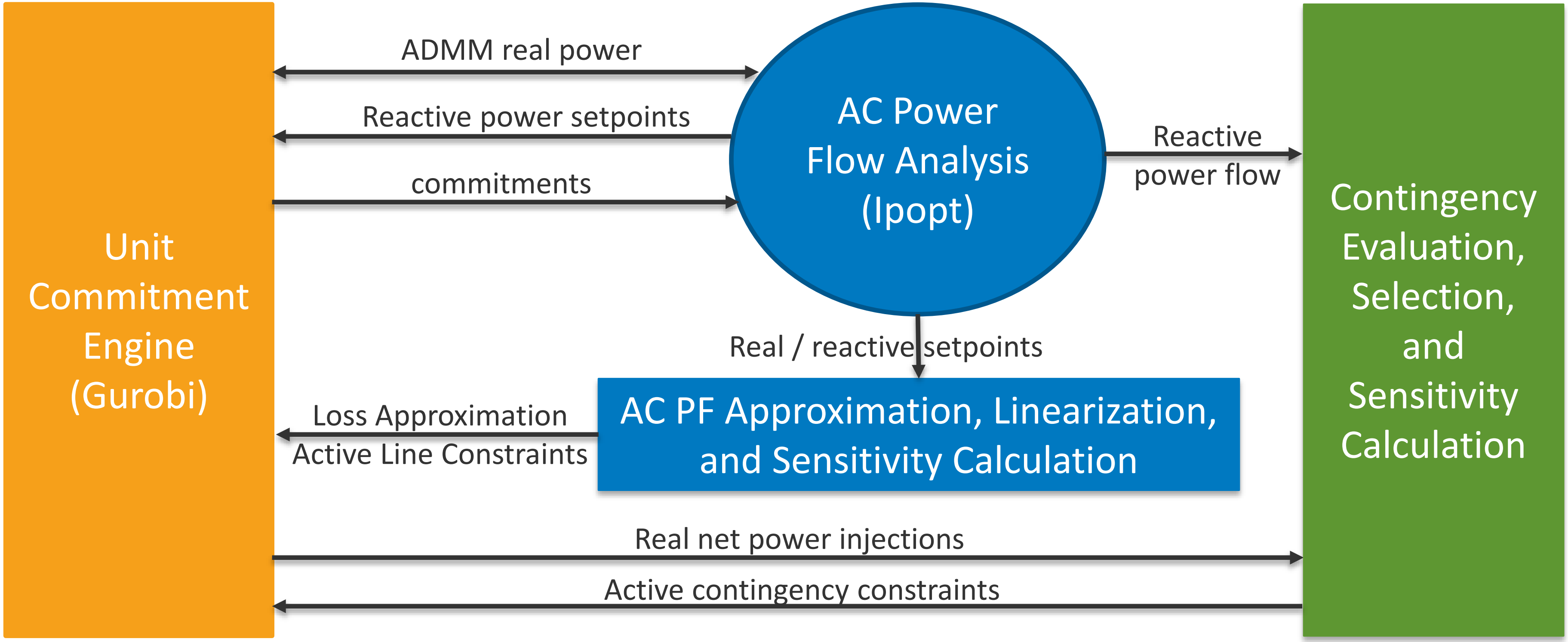
$$2\hat{p}_l^{\text{fr}}\left(\tilde{p}_l^{\text{fr,avg}} + 0.5\alpha_l^{\text{loss}} p^{\text{loss}}\right) - \left(\hat{p}_l^{\text{fr}}\right)^2 + \left(\hat{q}_l^{\text{fr}}\right)^2 \leq (s_l^{\max})^2 + 2s_l^{\max}s_l^{+} + 2\hat{s}_l^{+}s_l^{+} - (\hat{s}_l^{+})^2$$

$$2\hat{p}_l^{\text{to}}\left(\tilde{p}_l^{\text{fr,avg}} - 0.5\alpha_l^{\text{loss}} p^{\text{loss}}\right) - (\hat{p}_l^{\text{to}})^2 + (\hat{q}_l^{\text{to}})^2 \leq (s_l^{\max})^2 + 2s_l^{\max}s_l^{+} + 2\hat{s}_l^{+}s_l^{+} - (\hat{s}_l^{+})^2$$

Only add violated constraints!

Full details are in Eldridge 2020, Chapter 4

Solution Approach



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Contingency Analysis

Transmission Contingencies

- Electrical Engineering Requirement:
  - System needs to survive the loss of a single element
  - If a transmission line fails unexpectedly, other lines can become overloaded and trip off automatically, setting off a cascading series of failures
- Practice:
  - Only Monitor contingencies which do not disconnect the network
  - Maintain a watchlist of critical transmission contingencies
  - Typically, each contingency is just a single line failure

Transmission Contingencies

- In the GO3 formulation, transmission contingencies are linearized:

$$p_l^k = -B_l\left(\theta_{l(i)}^k - \theta_{l(j)}^k\right) \qquad \forall l \in L, \forall k \in K$$

$$p_k^k = 0 \qquad \forall k \in K$$

$$\sum_{c \in C_i} p_c + \sum_{l \in L_i^{fr}} p_l^k - \sum_{l \in L_i^{to}} p_l^k + \alpha_i p^{\text{loss}} = \sum_{g \in G_i} p_g \qquad \forall i \in I, \forall k \in K$$

$$\left(\left(p_l^k\right)^2 + \left(q_l^{\text{fr}}\right)^2\right)^{1/2} \leq s_l^{\text{max,ctg}} + s_{l,k}^+ \qquad \forall l \in L, \forall k \in K$$

$$\left(\left(p_l^k\right)^2 + (q_l^{\text{to}})^2\right)^{1/2} \leq s_l^{\text{max,ctg}} + s_{l,k}^+ \qquad \forall l \in L, \forall k \in K$$

Transmission Contingencies

- Too many constraints!
- Objective penalizes the average total line violation in each contingency plus the $k \in K$ with worst total line violations
  - Need to identify worst k, can leave the rest out of the UC model
- Still leaves a lot of constraints to check!

Transmission Contingencies

$$p_l^k = -B_l\left(\theta_{l(i)}^k - \theta_{l(j)}^k\right) \qquad \forall l \in L, \forall k \in K$$

$$p_k^k = 0 \qquad \forall k \in K$$

$$\sum_{c \in C_i} p_c + \sum_{l \in L_i^{fr}} p_l^k - \sum_{l \in L_i^{to}} p_l^k + \alpha_i p^{\text{loss}} = \sum_{g \in G_i} p_g \qquad \forall i \in I, \forall k \in K$$

$$\left(\left(p_l^k\right)^2 + \left(q_l^{\text{fr}}\right)^2\right)^{1/2} \leq s_l^{\text{max,ctg}} + s_{l,k}^+ \qquad \forall l \in L, \forall k \in K$$

$$\left(\left(p_l^k\right)^2 + \left(q_l^{\text{to}}\right)^2\right)^{1/2} \leq s_l^{\text{max,ctg}} + s_{l,k}^+ \qquad \forall l \in L, \forall k \in K$$

Critical observation: parts in blue are identical in every contingency

- Compute base-case flow under no contingency
- Contingency evaluation amounts to a rank-1 update to the base-case flow
  - This can be very fast, approximately the cost of $|K|$ simplex iterations on the base-case flow
- See Alsec et al. (1983) for details

Transmission Contingencies

- Once you evaluate the constraints, do some similar linear algebra to project out θ^k:

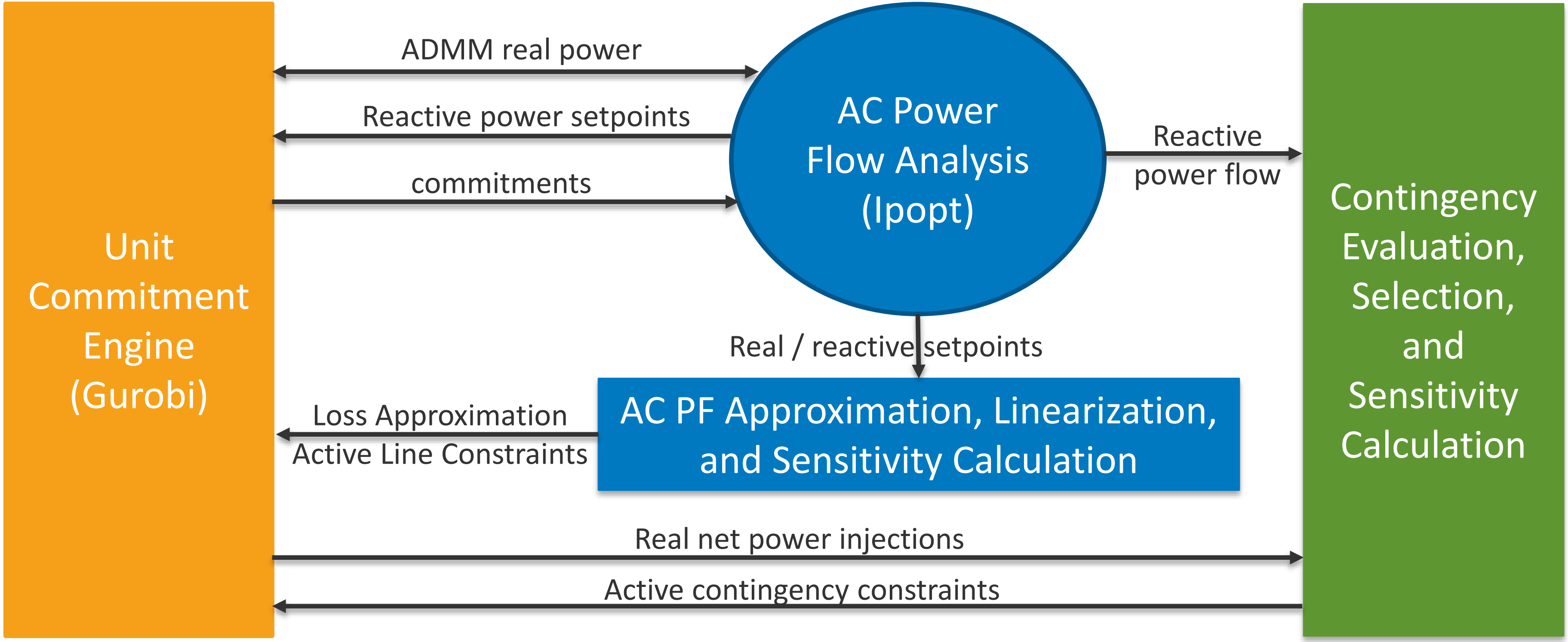
$$p_l^k = \alpha_{l,k}^0 + \sum_{c \in C} \alpha_{l,k}^c p_c + \sum_{g \in G} \alpha_{l,k}^g p_g \qquad \forall l \in L, \forall k \in K$$

$$\left(\left(p_l^k + \alpha_{l,k}^{\text{loss}} p^{\text{loss}}\right)^2 + \left(q_l^{\text{fr}}\right)^2\right)^{1/2} \le s_l^{\text{max,ctg}} + s_{l,k}^+ \qquad \forall l \in L, \forall k \in K$$

$$\left(\left(p_l^k + \alpha_{l,k}^{\text{loss}} p^{\text{loss}}\right)^2 + (q_l^{\text{to}})^2\right)^{1/2} \le s_l^{\text{max,ctg}} + s_{l,k}^+ \qquad \forall l \in L, \forall k \in K$$

- Compute a similar linearization / approximate of the line limits
- Cap the total number of contingency constraints allowed in UC

Solution Approach



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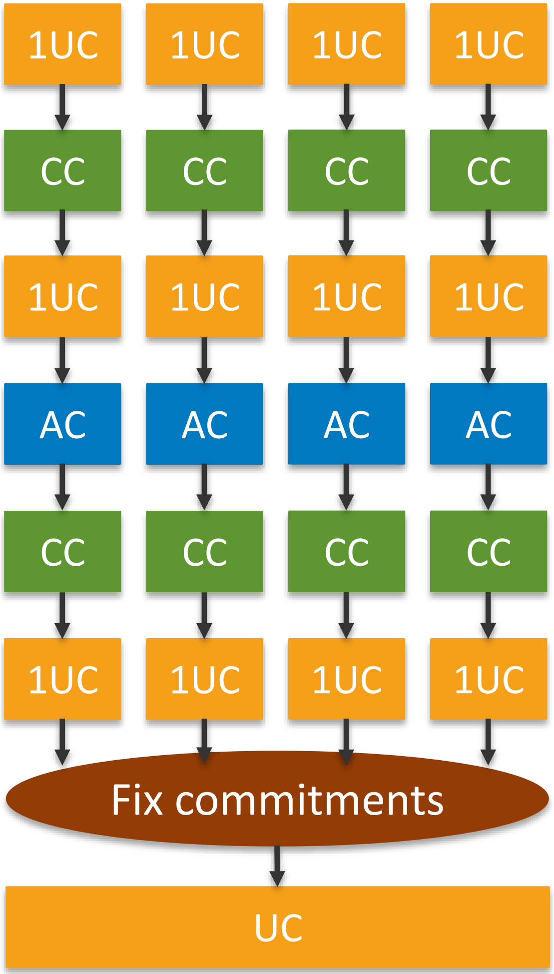
Unit Commitment Engine

Unit Commitment Engine

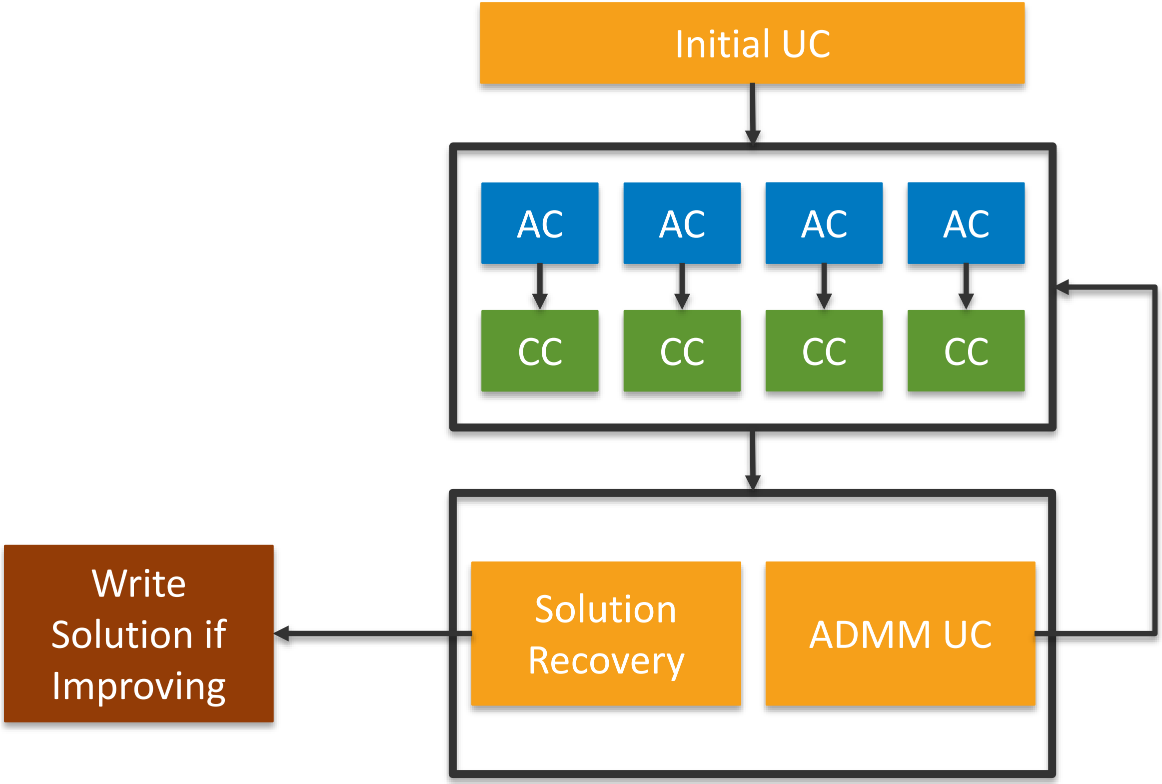
- Solved using Gurobi
- Competition formulation needed a few adjustments
  - Minimum up and downtime constraints were strengthened
  - Ramping constraints were simplified and strengthened
  - Result: initial copper plate UC was nearly integer feasible at root node (e.g., 50-100 fractional binaries out of ~100,000)
- Problem: solving the LP relaxation
  - Larger cases have thousands of dispatchable devices, which is an order of magnitude more than typical literature UC problems
  - Each device has ~20 constraints / variables *per time period*.
    - 18-period problem with 5,000 devices: 1.8 million variables / constraints
  - Preprocessing is key:
    - Do as much of it as possible when creating the model
    - Redundant reserve constraints, max energy constraints, ramping constraints, etc.

Heuristic Fixings & Warmstarting

- Solve single-time step UCs in parallel (1UC)
- Check contingencies for each time step in parallel
- Solve 1UC with contingency constraints
- Run AC PF analysis
- Check contingencies
- Solve 1UC with AC constraints and updated contingencies
- Fix generators whose commitment status changes at most once across the time horizon
- Warmstart full UC w and contingency constraints



Main Loop


Initial UC
AC
AC
AC
AC
CC
CC
CC
CC
Write Solution if Improving
Solution Recovery
ADMM UC

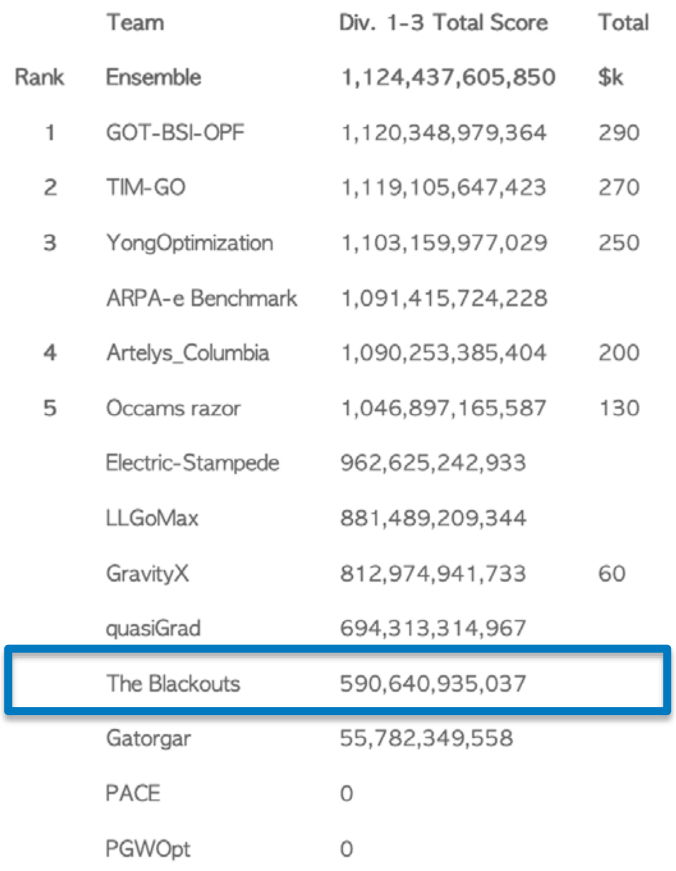
Competition Results

Event 4

Competition Scores

Six divisions total

- Div 1–3: D1, D2, D3 sum of objective function values
- Div 4–6: D1, D2, D3 total number of best scores



Rank	Team	Div. 1-3 Total Score	Total
	Ensemble	1,124,437,605,850	$k
1	GOT-BSI-OPF	1,120,348,979,364	290
2	TIM-GO	1,119,105,647,423	270
3	YongOptimization	1,103,159,977,029	250
	ARPA-e Benchmark	1,091,415,724,228	
4	Artelys_Columbia	1,090,253,385,404	200
5	Occams razor	1,046,897,165,587	130
	Electric-Stampede	962,625,242,933	
	LLGoMax	881,489,209,344	
	GravityX	812,974,941,733	60
	quasiGrad	694,313,314,967	
	The Blackouts	590,640,935,037	
	Gatorgar	55,782,349,558	
	PACE	0	
	PGWOpt	0	

Competition Scores

Six divisions total

- Div 1–3: D1, D2, D3 sum of objective function values
- Div 4–6: D1, D2, D3 total number of best scores

Rank	Team	Div. 4-6 Total	Total $k
1	YongOptimization	331	300
2	GravityX	105	260
3	TIM-GO	89	250
4	The Blackouts	56	200
5	GOT-BSI-OPF	47	70
	Artelys_Columbia	29	120
	Occams razor	4	
	Gatorgar	3	
	LLGoMax	3	
	ARPA-e Benchmark	0	
	Electric-Stampede	0	
	PACE	0	
	PGWOpt	0	
	quasiGrad	0	

Competition Scores

Six divisions total

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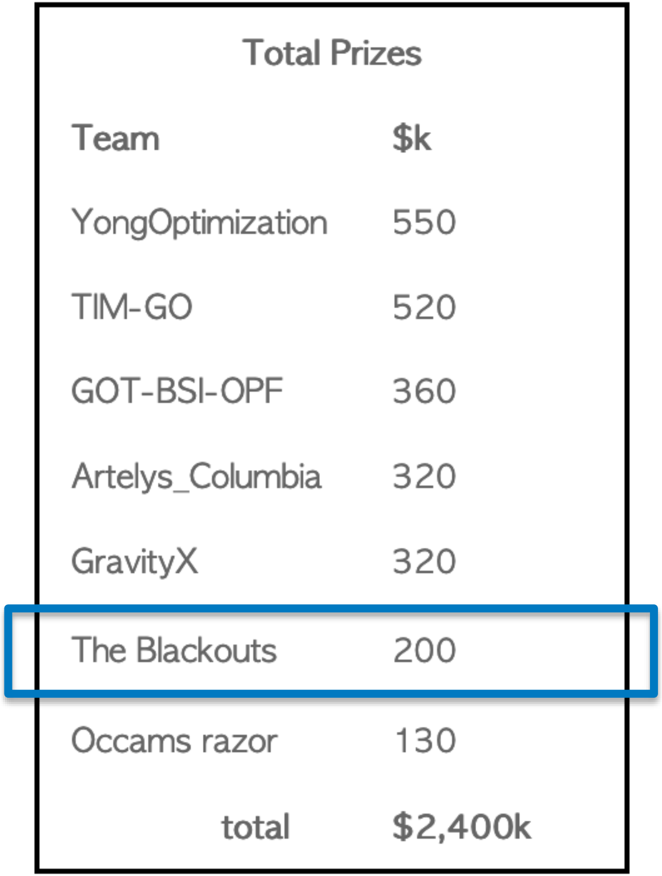
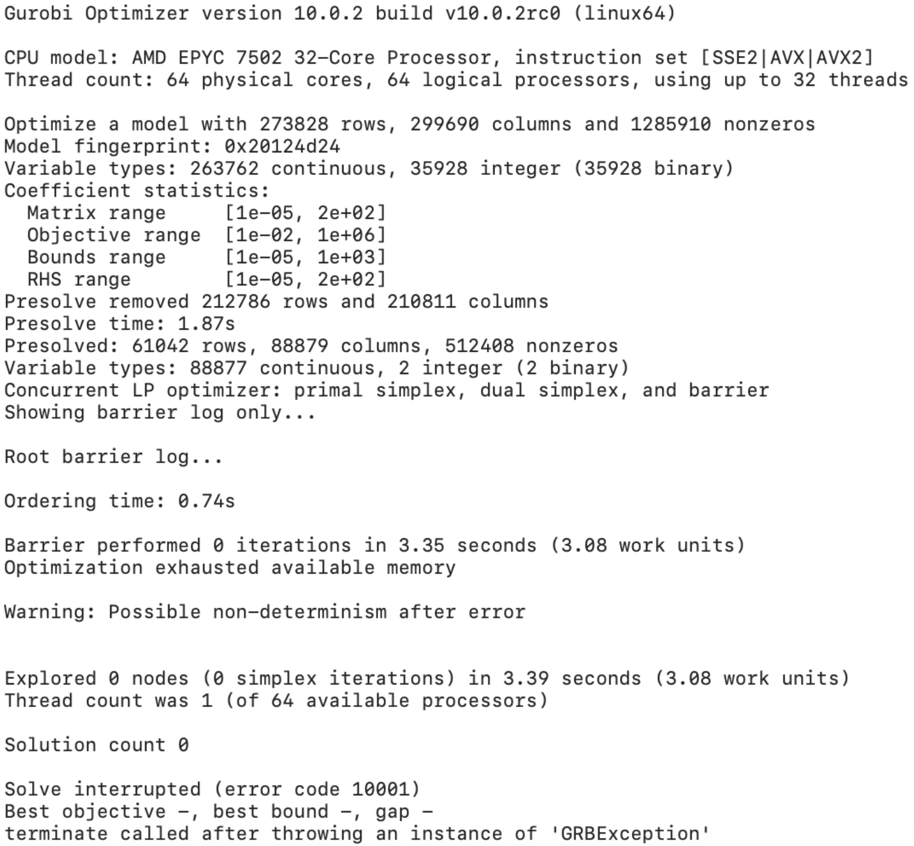


Total Prizes

Team	$k
YongOptimization	550
TIM-GO	520
GOT-BSI-OPF	360
Artelys_Columbia	320
GravityX	320
The Blackouts	200
Occams razor	130
total	$2,400k

Failure Modes

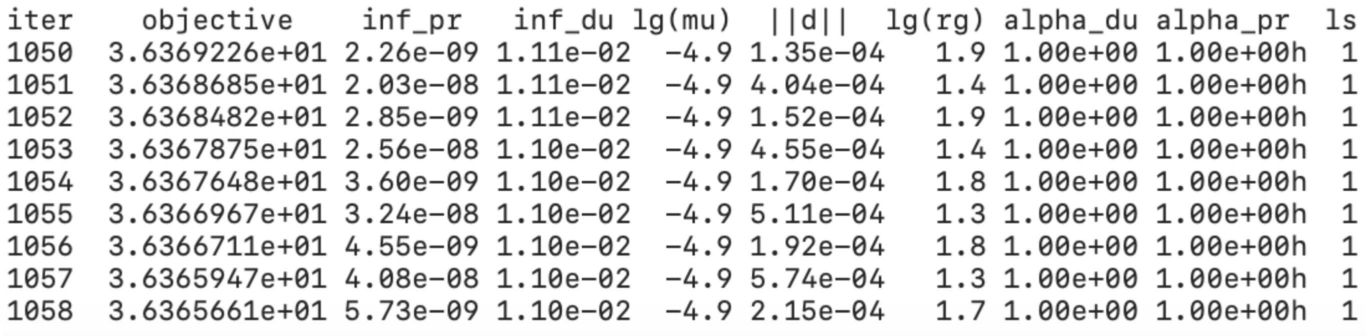
- Undiagnosed Gurobi Error on PNNL’s machines:
  - Tested code at UTK, NREL, LLNL – could not reproduce
  - PNNL compute node not obviously running out of memory



```
Gurobi Optimizer version 10.0.2 build v10.0.2rc0 (linux64)

CPU model: AMD EPYC 7502 32-Core Processor, instruction set [SSE2|AVX|AVX2]
Thread count: 64 physical cores, 64 logical processors, using up to 32 threads

Optimize a model with 273828 rows, 299690 columns and 1285910 nonzeros
Model fingerprint: 0x20124d24
Variable types: 263762 continuous, 35928 integer (35928 binary)
Coefficient statistics:
  Matrix range     [1e-05, 2e+02]
  Objective range  [1e-02, 1e+06]
  Bounds range     [1e-05, 1e+03]
  RHS range        [1e-05, 2e+02]
Presolve removed 212786 rows and 210811 columns
Presolve time: 1.87s
Presolved: 61042 rows, 88879 columns, 512408 nonzeros
Variable types: 88877 continuous, 2 integer (2 binary)
Concurrent LP optimizer: primal simplex, dual simplex, and barrier
Showing barrier log only...

Root barrier log...

Ordering time: 0.74s

Barrier performed 0 iterations in 3.35 seconds (3.08 work units)
Optimization exhausted available memory

Warning: Possible non-determinism after error


Explored 0 nodes (0 simplex iterations) in 3.39 seconds (3.08 work units)
Thread count was 1 (of 64 available processors)

Solution count 0

Solve interrupted (error code 10001)
Best objective -, best bound -, gap -
terminate called after throwing an instance of 'GRBException'
```

Failure Modes

- Failed to solve or took too much time for AC PF:
  - Winning team (YongOptimization) wrote their own interior point method



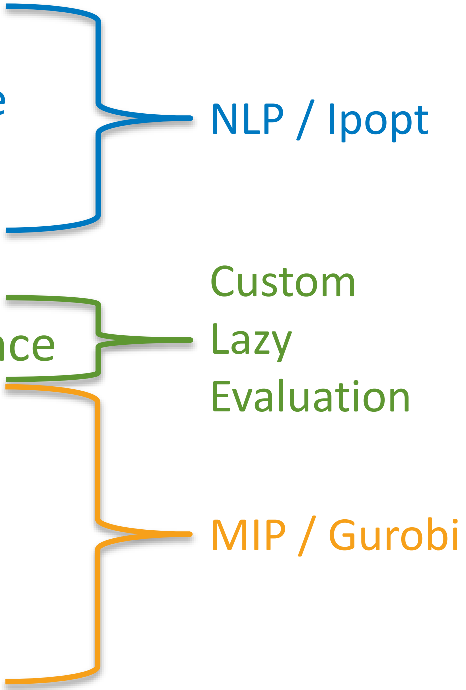
```
iter    objective    inf_pr   inf_du lg(mu)  ||d||  lg(rg) alpha_du alpha_pr  ls
1050  3.6369226e+01 2.26e-09 1.11e-02  -4.9 1.35e-04    1.9 1.00e+00 1.00e+00h  1
1051  3.6368685e+01 2.03e-08 1.11e-02  -4.9 4.04e-04    1.4 1.00e+00 1.00e+00h  1
1052  3.6368482e+01 2.85e-09 1.11e-02  -4.9 1.52e-04    1.9 1.00e+00 1.00e+00h  1
1053  3.6367875e+01 2.56e-08 1.10e-02  -4.9 4.55e-04    1.4 1.00e+00 1.00e+00h  1
1054  3.6367648e+01 3.60e-09 1.10e-02  -4.9 1.70e-04    1.8 1.00e+00 1.00e+00h  1
1055  3.6366967e+01 3.24e-08 1.10e-02  -4.9 5.11e-04    1.3 1.00e+00 1.00e+00h  1
1056  3.6366711e+01 4.55e-09 1.10e-02  -4.9 1.92e-04    1.8 1.00e+00 1.00e+00h  1
1057  3.6365947e+01 4.08e-08 1.10e-02  -4.9 5.74e-04    1.3 1.00e+00 1.00e+00h  1
1058  3.6365661e+01 5.73e-09 1.10e-02  -4.9 2.15e-04    1.7 1.00e+00 1.00e+00h  1
```

Failure Modes

- ???
  - No output written to console
  - Software logs output before even reading instance file

Suboptimality

- Multiperiod security constrained AC unit commitment
  - Nonlinear AC power flow / balance
    - Real/reactive power production/consumption and balance
    - Voltage magnitude/angle
    - Discrete shunt steps
    - Topology optimization
  - Branch contingencies using linear real power flow / balance
  - Detailed generator/load modeling
    - Startup/shutdown
    - Reactive power limits determined by real power output
    - Minimum up/down requirements
  - Suite of reserve products (both generator and load)



NLP / Ipopt

Custom
Lazy
Evaluation

MIP / Gurobi

Suboptimality

Not enough iterations

- Need around 10 for a high-quality solution
- Sometimes UC is too slow / too big
- Sometimes AC PF is slow

Reflections

Reflections

- Competitions go very, very quickly
  - Never had enough time to thoroughly test and evaluate
- Compiling and executing software on a system without direct access to debug is exceedingly difficult
  - Debugging MPI code is also hard!
- Many competitors implemented simpler, one-shot heuristics

Reflections

- Despite the various difficulties, our method performed well

- Biggest holdups:
  - Undiagnosed Gurobi error
  - Lack of transmission switching method

- Future work:
  - Establish baseline for submitted code
  - Enable / enhance transmission switching
  - More robust AC power flow solves

References

Eldridge, Brent C. *Algorithms and economic analysis for the use of optimal power flow and unit commitment in wholesale electricity markets*. Diss. The Johns Hopkins University, 2020.

Garcia, Manuel, Ross Baldick, and Shams Siddiqi. "A general economic dispatch problem with marginal losses." *2019 American Control Conference (ACC)*. IEEE, 2019.

Alsac, O., B. Stott, and W. F. Tinney. "Sparsity-oriented compensation methods for modified network solutions." *IEEE Transactions on Power Apparatus and Systems* 5 (1983): 1050-1060.

Q&A

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