GO Competition 3: YongOptimization Team - Solutions, Experiences, and Thoughts

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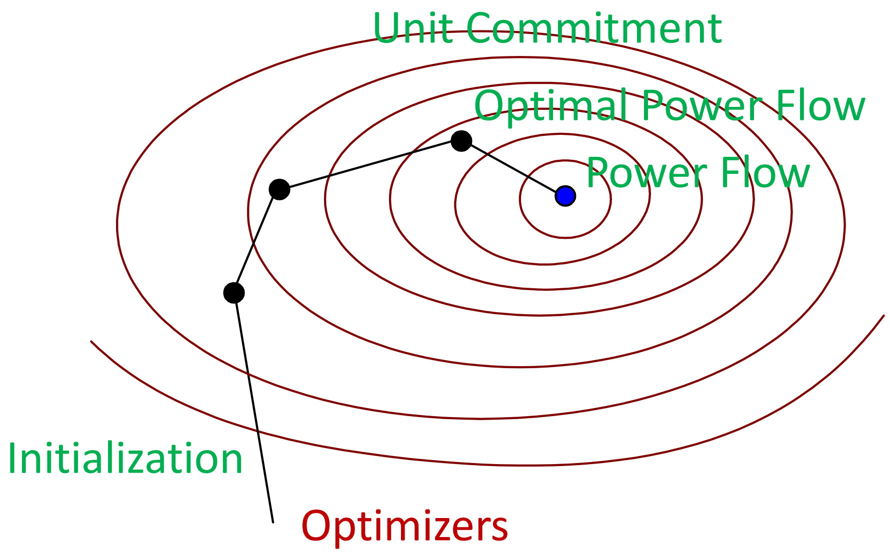
DOE ARPA-E GO3 Discussion Meeting

Part I: Algorithms and Results



GO1 & GO2: Success and Lessons Learned

- GO1: Single-period AC Optimal Power Flow (2018)
  - IPOPT as nonlinear optimization solver
  - A mistake on the output/printing module for the Network_25*-060, 20 scenarios
  - Top 10 Winner

- GO2: Single-period AC Optimal Power Flow with Unit Commitment and Line Switching (2020)
  - Successive linear programing with mixed integer variables (Gurobi as MILP solver)
  - No time to develop module to perfectly handle the power mismatches at buses
  - Not top 5 Winner

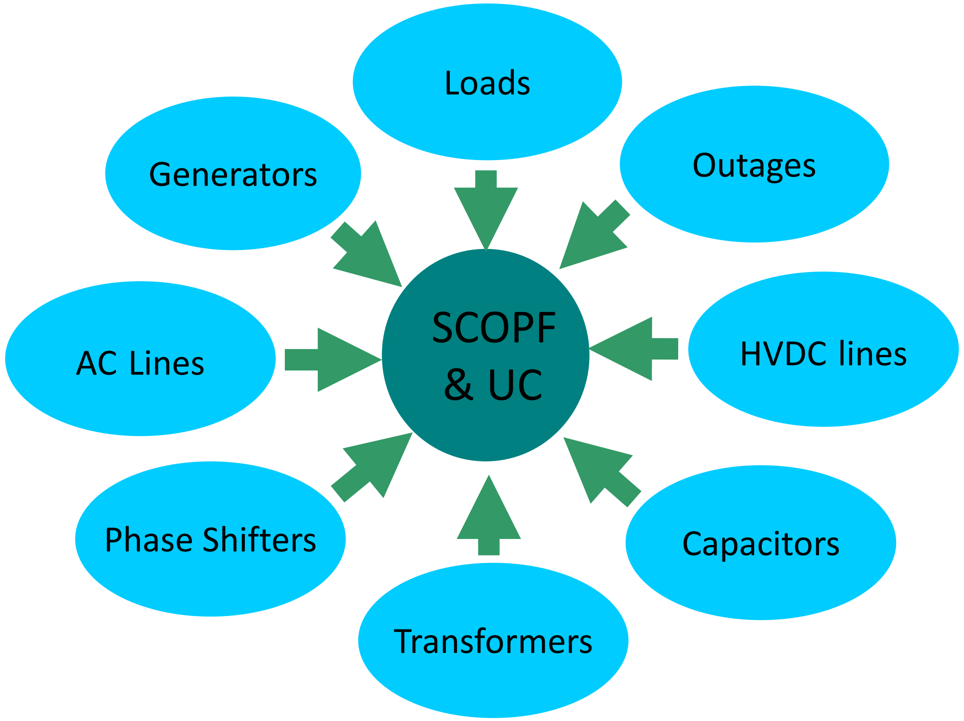
GO3 Problems

GO3: Multi-period AC Optimal Power Flow with Unit Commitment and Line Switching (2022)

- **Market Surplus Objective (for D1, D2, D3)**
  - Maximize:

    Total Market Surplus = Base Case Market Surplus + Worst Case and Average Case of Post-Contingency Outcomes.
- **Constraints**
  - Bus real and reactive power balance and voltage limits
  - Zonal reserve requirements
  - Device on-off status and related constraints
  - Producing and consuming devices: startup, shutdown, dispatchable power, ramping, reserve, max/min energy over multiple intervals
  - Shunt real and reactive power constraints
  - AC & DC branch flow limits
  - Post-contingency AC power flow limits

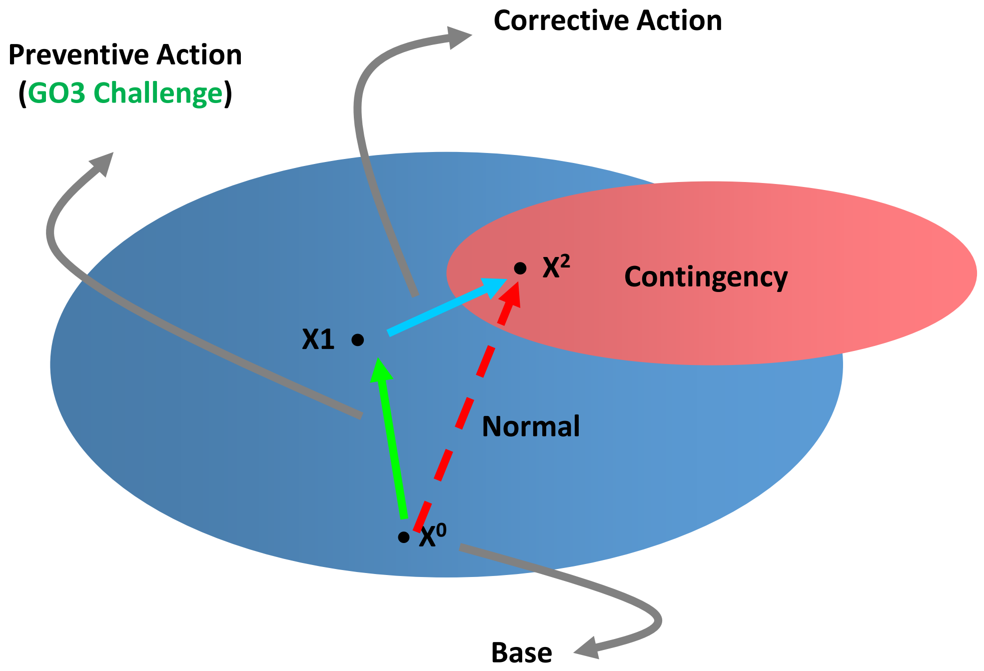
- D1: Real-Time Market with 8-hour look ahead -- 8 0.25-hour periods, 8 0.5-hour periods, 2 1-hour periods
- D2: Day-Ahead Market with 48-hour look ahead -- 48 1-hour periods
- D3: Weekly Scheduling Week-Ahead Advisory with 7-day (168-hour) look ahead -- 42 4-hour periods



GO3 Challenges

➢ **Challenges**

- Convergence of nonlinear ACOPF problem
- Speed of large-scale mixed integer UC problem
- Multiple periods study
- Numerous creditable contingencies
- Implementation
- Infeasibility issues (tolerance 1.0e-8!!)
- Submission ??



A fast and high-quality solution to the large-scale, mixed-integer, nonlinear, non-convex, and multi-period optimization problem

Our Targets and Thoughts

- **Targets**
  - Top Performer
  - Large-scale Network
  - Fast Solution
  - Pre-Production Software – Never Fail

- **Thoughts**
  - Problem Reformulation
  - Decomposition and Mathematical Optimization
  - Our Own Nonlinear Optimization Solver
  - Modular Software Architecture
  - Risk Management
  - Clear Roles and Responsibilities of Team Members

Fig: Our Targets and Thoughts

Software Tools Used and Developed

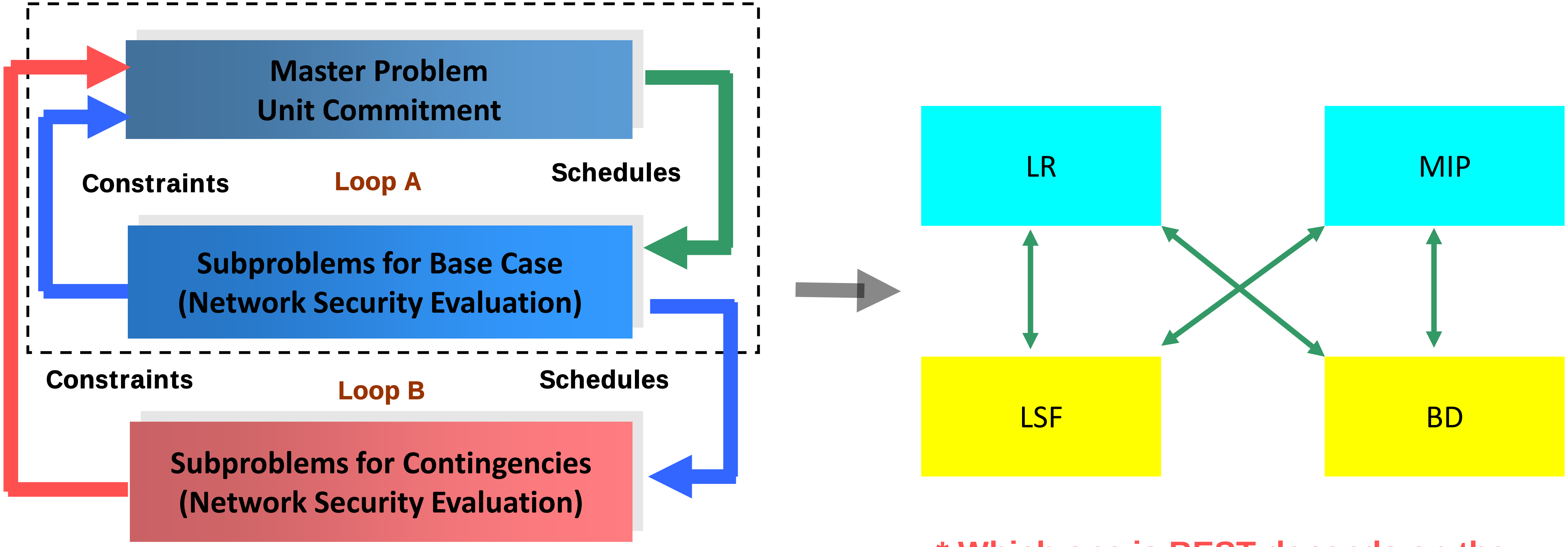
- Develop codes in C language on Linux (CentOS 7.8.2003)
- Tested the codes on 16 processor cores in a desktop computer with Intel® Core™ i9-12900K processor (3.2 GHz) & 64 processer cores in the PNNL HPC.
- Use OpenMPI 4.1.4 to pass messages among multiple processor cores.
- Use Gurobi (10.0.2) (from Gurobi Optimization) as the MILP solver.
- Use PARDISO (8.0) (from Panua Technologies) as the linear solver.
- Use open source Json-C for input and output Json files.
- Develop Fast Unit Commitment Module
- Develop Multi-period AC Optimal Power Flow Module
- Develop Online Contingency Analysis Module
- Develop Dispatchable Power Flow Module

GUROBI OPTIMIZATION

Panua Technologies

json-c

Background - AC-SCOPF with UC Solution



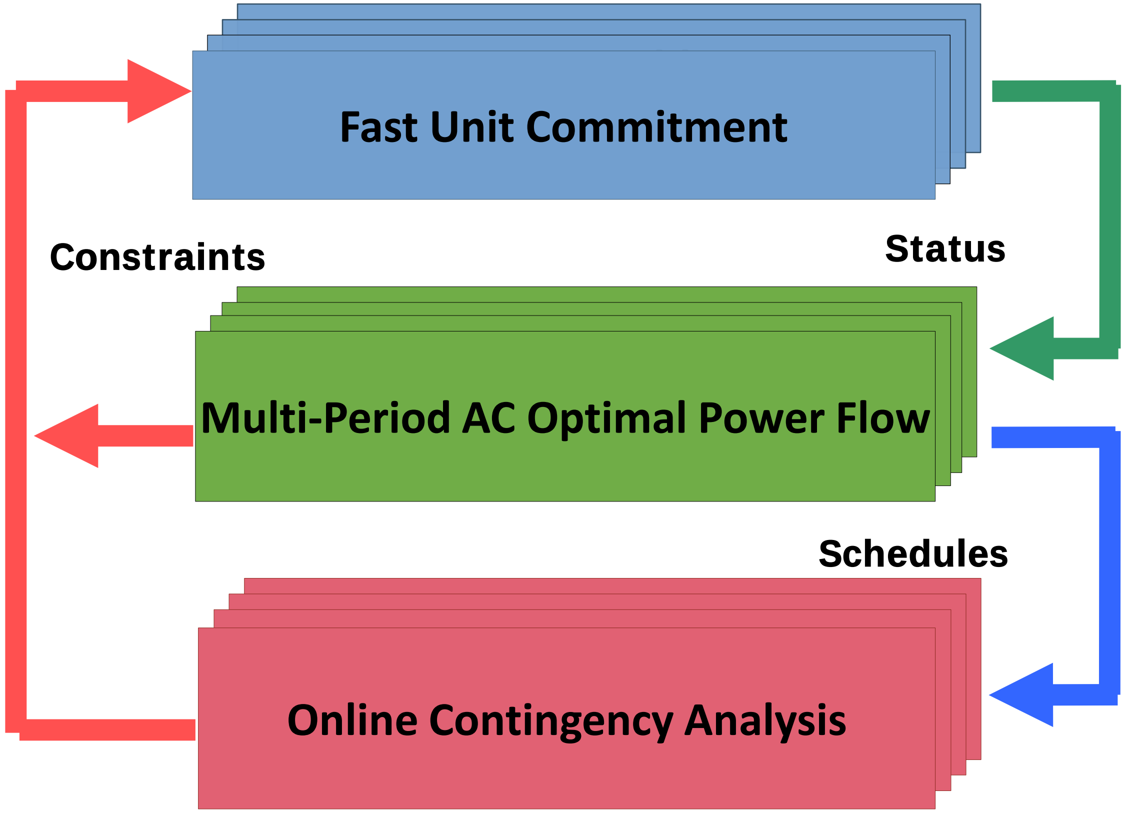
*** Which one is BEST depends on the system and solution conditions ***

Unit Commitment: Lagrangian Relaxation based & MIP based
Network Security Evaluation: Linear Sensitivity based & Benders Cut based

Y. Fu, Z. Li, and L. Wu, "Modeling and Solution of the Large-Scale Security-Constrained Unit Commitment," *IEEE Transactions on Power Systems*, Vol. 28, No. 4, pp. 3524-3533, November 2013

Proposed Fast AC-SCOPF with UC Solution on HPC

Flowchart



A good/reasonable UC result will provide ACOPF more chances to get a solution without any power mismatches and violations.

Constraints

- Device on-off status and related constraints
- System-level real and reactive power balances
- Producing and consuming devices: startup, shutdown, dispatchable power, ramping, reserve, max/min energy over multiple intervals
- Zonal reserve requirements

- Producing and consuming devices: dispatchable power, ramping, reserve, max/min energy over multiple intervals
- Zonal reserve requirements
- Shunt real and reactive power constraints
- Bus real and reactive power balance and voltage limits
- AC & DC branch flow limits

- Post-contingency AC power flow limits

Fast Unit Commitment Modeling and Solution

- **Challenges**
  - No historical information, no periodic warm-start point
  - Relations between real and reactive power outputs of devices
  - Huge amount of binary/continuous variables and constraints
  - “Unpredictable” calculation time

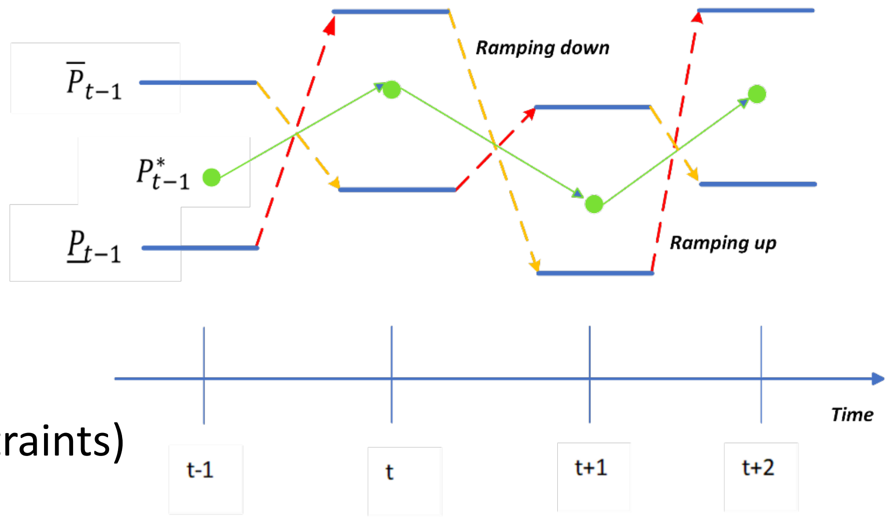
Lock/Unlock Device Status

Devices	Periods (1-18)
1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
3	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
4	0 0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 0 0 0
5	0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 0
6	0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0
7	0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0
8	0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0
9	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
10	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
11	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1

- **Solutions**
  - LR-based fast UC and initial study (e.g. base/peak devices, system losses, critical branches) in 100 seconds
  - Considering both real power and reactive power constraints for both device- and system- levels
  - Including power losses (e.g. 1% - 10% of total loads)
  - Remodel MIP-based UC (e.g. 3-binary model to 1-binary model, reduce intermediate variables, combine constraints)
  - Lock/Unlock status of devices (e.g. commit devices with high economic & security indices)
  - Inactive constraints elimination (e.g. reserve requirements for top peak devices only, branch flow limits for critical branches only)

Multi-period ACOPF Modeling and Solution

- Challenges
  - Huge amount of continuous variables and nonlinear constraints
  - Various requirements on power reserves
  - A multiple-period study with coupling constraints between periods
  - Reliable and high-quality nonlinear optimization solver



- Solutions
  - Remodel ACOPF (e.g. reduce intermediate variables, combine constraints)
  - Eliminate inactive constraints (e.g. Non-critical branch flow limits)
  - Add linear sensitivity based branch flow limits for critical contingencies only
  - Consider both power generation/consumption and reserve constraints
  - Determine power “upper” and “lower” bounds of devices for ramping to decouple multiple-period ACOPF
  - Develop a primal-dual interior point method with Pardiso as a linear solver (initial point, sparse matrix techniques, step size updates, scaling, etc.) for single-period ACOPF
  - Conduct post-processing modules to improve/verify the results
    - ✓ Dispatchable power flow (e.g. fast-decoupled, factorization, adjustable power outputs)
    - ✓ Real Power reserve optimization
    - ✓ Reactive power reserve optimization

Online Contingency Analysis

- **Challenges**
  - Many, many creditable contingencies (e.g. 26,870 contingencies for a 23,643-bus network)
  - Minimize worst contingency penalty
  - A time-consuming task
  - Memory issue (e.g. 26,870 contingencies × 48 periods × 33,739 branches)
- **Solutions**
  - Covert nodal power balance based to Shift Factor DC based network model
  - Calculate Shift Factor for base network model (SF_base)
  - Online update Shift Factor for each contingency (SF_ctgc)
  - Model violation constraints for critical branches for critical contingencies

SF for Ctgc

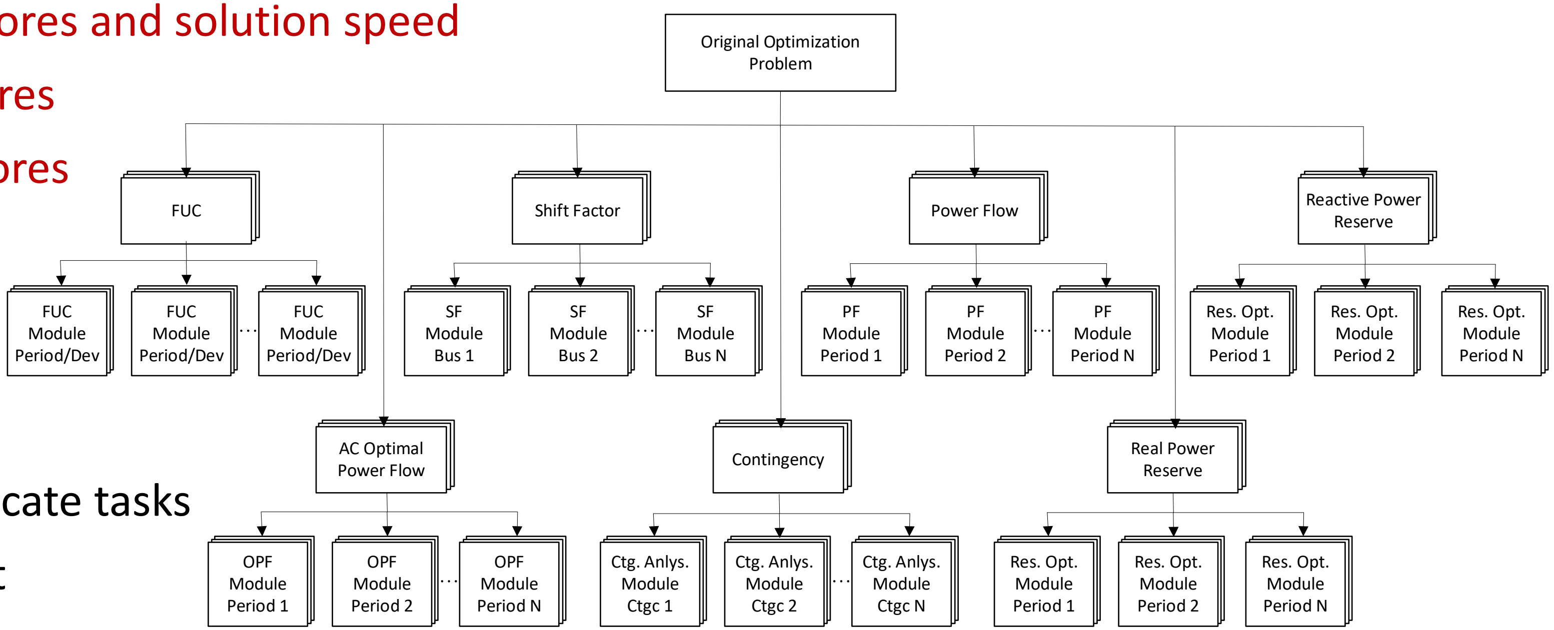
SF for base

$$
\begin{aligned}
\mathbf{SF}^{(\mathbf{O})\to s1}_{\mathbf{M1},(L1\times N1)} &= \mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{M1},(L1\times N1)} + \mathbf{LODF}^{\mathbf{0}\to s1}_{\mathbf{M1,O},(L1\times O)} \times \mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{O,B1},(O\times N1)} \\
&= \mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{M1},(L1\times N1)} + \mathbf{PTDF}^{\mathbf{0}\to s1}_{\mathbf{M1,O},(L1\times O)} \times [\mathbf{E}_{(O\times O)} - \mathbf{PTDF}^{\mathbf{0}\to s1}_{\mathbf{O,O},(O\times O)}]^{-1} \\
&\times \mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{O,B1},(O\times N1)} = \mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{M1},(L1\times N1)} + (\mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{M1,O\_from},(L1\times O)} - \mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{M1,O\_to},(L1\times O)}) \\
&\times [\mathbf{E}_{(O\times O)} - (\mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{O,O\_from},(O\times O)} - \mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{O,O\_to},(O\times O)})]^{-1} \times \mathbf{SF}^{\mathbf{0}\to s1}_{\mathbf{O,B1},(O\times N1)}
\end{aligned}
$$

Network	Scenario	Contingencies	Speed (Seconds) on 25 cores
C3E3N00617D1	1	562	2
C3E3N01576D1	27	219	2
C3E3N04224D1	131	2,313	18
C3E3N06049D1	22	3,884	11
C3E3N06717D1	41	2,670	13

Parallel Implementation

- Challenges
  - Tradeoff between number of used cores and solution speed
  - Communication latency between cores
  - Computing load-balancing among cores
- Solutions
  - Use 25 cores for D1, D2, and D3
  - Provide input data to all cores
  - Use a Round-Robin algorithm to allocate tasks
  - Conduct dynamic time management



- Multiple Parallel Tasks Implemented on HPC (25 cores)
  - Fast unit commitment
  - Multi-period AC optimal power flow
  - Shift factor calculation (e.g. 33,739 branches × 23,643 buses in 5 sec.)
  - Online contingency analysis
  - Dispatchable power flow
  - Real power reserve optimization
  - Reactive power reserve optimization

Line Switching Optimization

- Challenges
  - UC and LS handling
  - Because of congestions, losses, and/or convergence
  - Network connectivity for both base case and contingencies
- Solutions
  - Conduct UC → LS
  - Select line candidates
  - Use linearized ac network model with switchable line as pseudo generators at its ending buses
  - Integrate connectivity constraints into LS (only **ONE** for each base case/each contingency case)

5*,***,***?

Network	Scenario	Without LS ($)		With LS ($)	
		Best Score	Our Score	Best Result	Our Result
C3E4N00073D2	991	**20,688,796**	**0 (Negative)**	**58,977,389**	**58,977,389**
C3E4N00073D2	992	**20,784,063**	**0 (Negative)**	**58,970,939**	**58,970,939**
C3E4N00073D2	996	**20,693,131**	**0 (Negative)**	**58,977,389**	**58,977,389**
C3E4N00073D2	997	**19,489,500**	**0 (Negative)**	**58,970,940**	**58,970,940**

Table. Difficult bus-73 Scenarios

high line shunt charging susceptance b ?

Selected GO3 Final Event Results from 667 scenarios

Network Model	Scenario	Obj ($)	Time (sec.)	Buses	Dispatchable Devices		Shunts	Branches			Zones		Contingencies
								AC Branches		DC Lines			
					Loads	Generators		AC Lines	Transformers		Real Power	Reactive Power	
73 D1	309	28,277,399	12	73	51	154	73	105	15	1	1	1	2
617 D1	3	27,216,883	103	617	405	94	22	723	130	0	10	10	562
1576 D1	15	183,841,776	263	1576	1451	615	68	2270	157	2	2	2	147
2000 D1	33	216,417,954	529	2000	544	1350	157	2345	861	0	4	10	2756
4224 D1	2	91,545,159	188	4224	1673	478	436	2605	2325	0	2	2	2313
6049 D1	13	124,863,668	462	6049	3368	406	236	4920	3086	0	6	6	3902
6717 D1	44	159,189,217	622	6717	5095	731	634	7173	1967	0	9	12	2670
8316 D1	203	206,097,985	603	8316	4457	1126	1179	7723	4249	0	7	7	6289
23643 D1	3	104,073,565	548	23643	11731	6274	2717	23797	9942	1	4	5	26870
73 D2	303	147,785,503	40	73	51	154	73	105	15	1	1	1	2
617 D2	14	265,243,886	248	617	405	94	22	723	130	0	10	10	562
2000 D2	5	755,259,134	2328	2000	544	1350	157	2345	861	0	4	10	2756
4224 D2	11	548,193,558	903	4224	1673	478	436	2605	2325	0	2	2	2313
6049 D2	7	608,986,314	2400	6049	3368	406	236	4920	3086	0	6	6	3902
6717 D2	2	798,048,811	1781	6717	5095	731	634	7173	1967	0	9	12	2670
8316 D2	115	1,823,426,485	2873	8316	4457	1126	1179	7723	4249	0	7	7	6289
23643 D2	3	600,577,211	1540	23643	11731	6274	2717	23797	9942	1	4	5	26870
73 D3	327	575,050,977	29	73	51	154	73	105	15	1	1	1	2
617 D3	32	906,774,710	133	617	405	94	22	723	130	0	10	10	562
1576 D3	103	1,482,513,082	1109	1576	1451	615	68	2270	157	2	2	2	147
2000 D3	7	2,449,513,145	2052	2000	544	1350	157	2345	861	0	4	10	2756
4224 D3	25	1,615,466,556	650	4224	1673	478	436	2605	2325	0	2	2	2313
6049 D3	31	2,384,371,514	2306	6049	3368	406	236	4920	3086	0	6	6	3902
6717 D3	26	3,171,015,158	1401	6717	5095	731	634	7173	1967	0	9	12	2670
8316 D3	103	4,123,489,313	3513	8316	4457	1126	1179	7723	4249	0	7	7	6289
23643 D3	3	2,158,212,496	1848	23643	11731	6274	2717	23797	9942	1	4	5	26870

GO3 Final Event Result

Rank	Team	Division 1 Score
1	GOT-BSI-OPF	45,197,083,660
2	**YongOptimization**	**44,591,294,554**
3	TIM-GO	43,872,727,267
4	Occams razor	42,019,935,603
5	Artelys_Columbia	41,955,425,465

Rank	Team	Division 2 Score
1	GOT-BSI-OPF	162,941,475,726
2	TIM-GO	162,270,256,651
3	**YongOptimization**	**160,165,088,341**
4	Artelys_Columbia	157,359,267,058
5	GravityX	156,131,225,903

Rank	Team	Division 3 Score
1	TIM-GO	912,962,663,505
2	GOT-BSI-OPF	912,210,419,977
3	**YongOptimization**	**898,403,594,134**
4	Artelys_Columbia	890,938,692,881
5	Occams razor	859,382,611,148

Rank	Team	Division 4 Best Score Counts
1	**YongOptimization**	**156**
2	TIM-GO	39
3	GravityX	37
4	GOT-BSI-OPF	28
5	The Blackouts	16

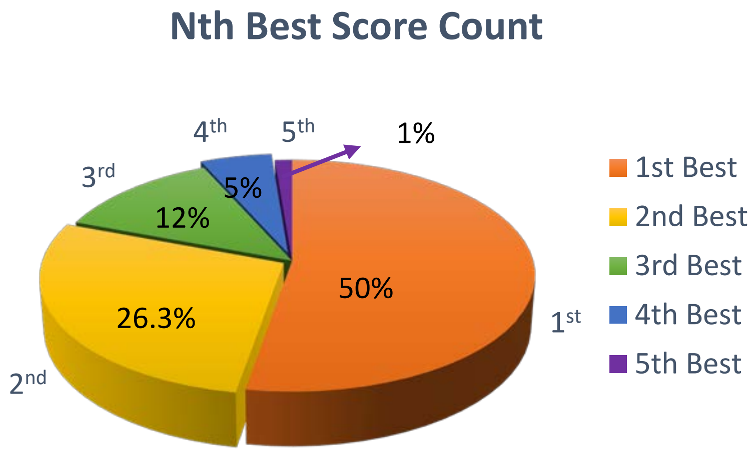
Rank	Team	Division 5 Best Score Counts
1	**YongOptimization**	**78**
2	GravityX	38
3	TIM-GO	23
4	The Blackouts	18
5	Artelys_Columbia	17

Rank	Team	Division 6 Best Score Counts
1	**YongOptimization**	**97**
2	GravityX	30
3	TIM-GO	27
4	The Blackouts	22
5	Artelys_Columbia	10

Solution Speed: Ranks second in terms of solution speed.

- **D1**, **D2**, and **D3** rankings are determined based upon the total objective value of all scenarios in each division.
- **D4**, **D5**, and **D6** rankings are based on the count of top scores for each scenario in D1, D2, and D3.
- **283** scenarios in D1, **192** in D2, and **192** in D3 for a total of **667** scenarios.

GO3 Final Event Result Analysis



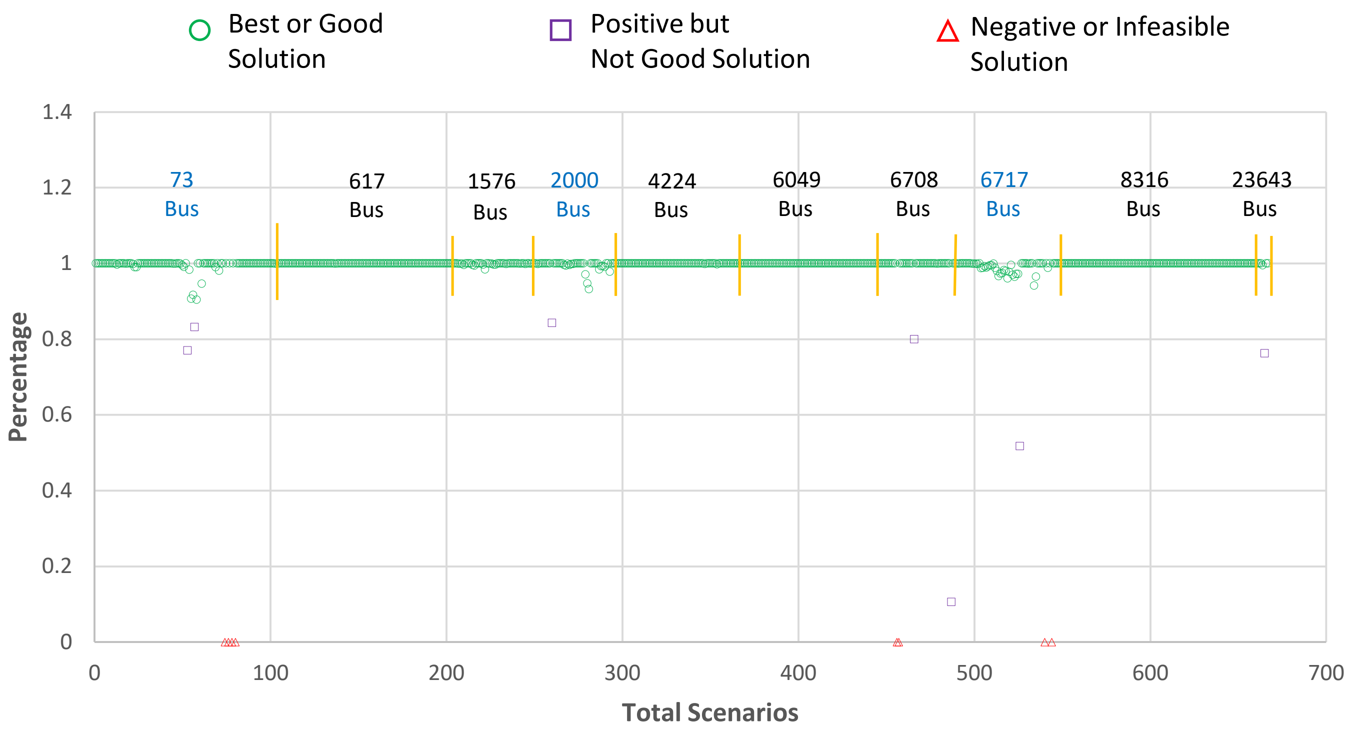


Fig. Objective Value Compared to Best Score (Percentage)

- Positive but Not Good Solution [0%, 90%]: There were 7 cases out of 667 where we did not get a good enough score.
- Negative or Infeasible Solution: There were 8 cases out of 667 where we did not get a positive score.

Update on Final Event Results
(Positive but Not Good Solution Scenarios)

Case	Scenario	Event 4 Score	New Score	Analysis
1	C3E4N00073D2-S913-SW1	45,225,393	58,658,743	Adjust the parameter for the fast UC module.
2	C3E4N00073D2-S915-SW1	48,859,788	58,639,581	
3	C3E4N02000D1-S018-SW1	180,629,884	214,491,150	Adjust the parameter for zonal reserve constraints.
4	C3E4N06708D2-S023-SW1	2,712,333,566	33,94,983,386	Industry case. Adjust the parameter for the ACOPF module.
5	C3E4N06708D3-S228-SW1	1,936,134,677	18,346,063,294	
6	C3E4N06717D1-S105-SW1	114,519,755	190,848,268	Adjust the parameter for the fast unit commitment module.
7	C3E4N23643D1-S004-SW1	69,793,156	96,212,707	Adjust the parameter for the ACOPF module.

Update on Final Event Results

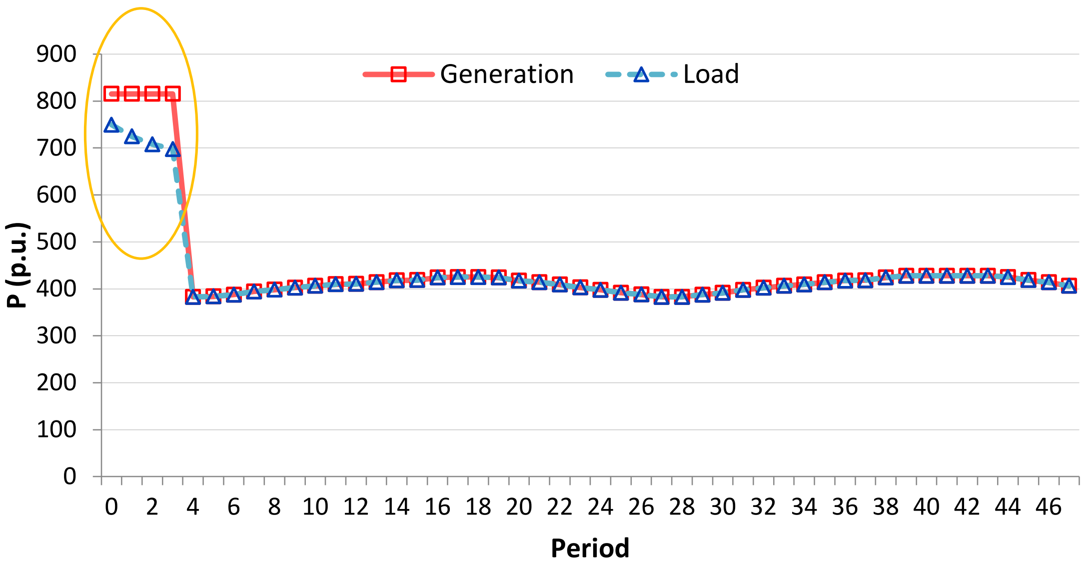
(Negative or Infeasible Scenarios)

Case	Scenario	Event 4 Score	New Score	Analysis
1	C3E4N00073D2-S991-SW0	0 (Negative Objective)	Not converged	ACOPF cannot converge when line switching is not allowed. high line shunt charging susceptance b ?
2	C3E4N00073D2-S992-SW0	0 (Negative Objective)	Not converged	
3	C3E4N00073D2-S996-SW0	0 (Negative Objective)	Not converged	
4	C3E4N00073D2-S997-SW0	0 (Negative Objective)	Not converged	
5	C3E4N06717D2-S044-SW1	0 (Infeasible)	905,093,599	Regarding the precision threshold. A bug!
6	C3E4N06717D2-S068-SW1	0 (Infeasible)	1,330,249,620	
7	C3E4N06708D1-S016-SW0	0 (Negative Objective)	519,884,312	Industry case. Adjust the parameter for the ACOPF module.
8	C3E4N06708D1-S016-SW1	0 (Negative Objective)	519,884,312	

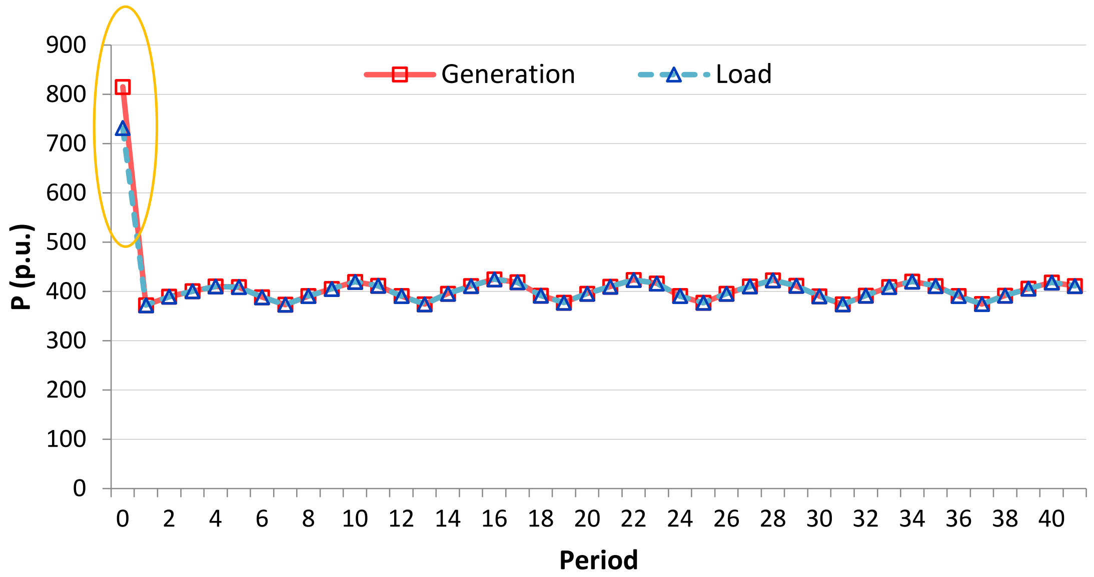
Update on Final Event Results

(No positive score so far)

Case	Scenario	Event 4 Score	New Score	Analysis
1	C3E4N23643D2-S004-SW1	0 (Negative Objective)	0 (Negative Objective)	Periods 0 – 3 can not converge. The generation cannot match the load well in the periods 0 -3, and they are much higher than the remaining periods.
2	C3E4N23643D3-S004-SW1	0 (Negative Objective)	0 (Negative Objective)	Period 0 can not converge. The generation cannot match the load well in the period 0, and they are much higher than the remaining periods.



C3E4N23643D2-S004-SW1



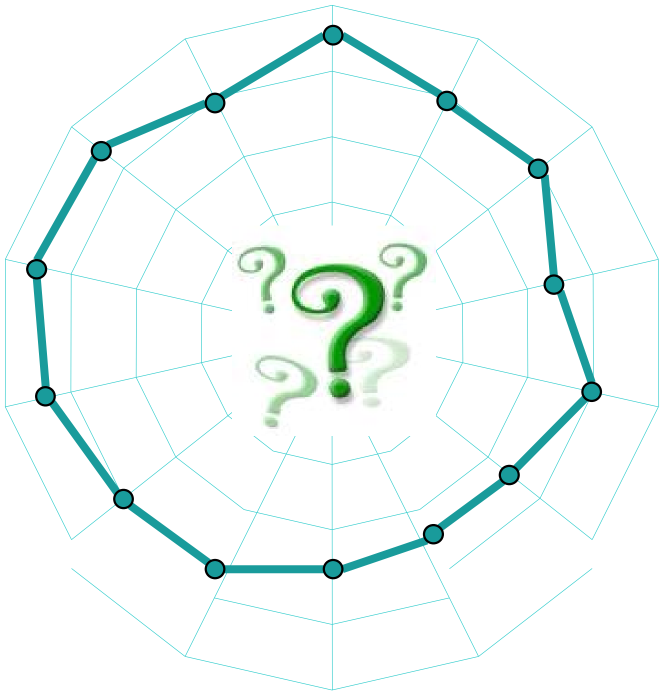
C3E4N23643D3-S004-SW

A conflict between power balance and reserve requirement (regulation up)?

Future Improvements

- Optimize codes and memory usage
- Leverage more cores/processors for HPC implement to speedup the solution
- Enhance ACOPF solution to make it more efficient
- Accelerate UC solution, especially for the network 23,643 for D1
- Improve and fully test the line switching module to show more benefits

Part II: Questions & Answers



Questions regarding the Algorithms

1. What process did your team use in deciding the algorithmic approach?

Answer:

Step 1: Review and Analyze Problems and Requirements:

- Conducted a thorough review of problem formulation and input/output data structure.
- Performed an in-depth analysis of project requirements, including objectives, constraints, and data nature.
- Considered specific needs, including performance metrics, computational resources, time limits, software availability.

Step 2: Review Our Published/existing Algorithms/Solutions:

- Evaluated our methodologies to ensure their effectiveness in solving the problem.
- Make sure that the team members have the first hand experience on the algorithms/solutions.

Step 3: Develop Algorithms:

- Defined proper problem modules and use the most appropriate algorithms/software to solve them.
- Tested our algorithms using the GO3 datasets and ensure the scalability, efficiency, and stability of our solution.

Step 4: Improve Our Solutions with Event Feedback:

- Conducted scenario-based comparative analysis focusing on solution speed and optimality.
- Tune the algorithm parameters and adjust solution strategies.

Step 5: Final Decision:

- Finalize the algorithms with balanced trade-offs.
- Submit to fulfill the competition goals.

Questions regarding the Algorithms

2. Did your team consider/use a hybrid approach by running different types of algorithms in parallel?

Answer: NO backup/alternative algorithms in parallel.

Potential Benefits	Our Thoughts
• Enhanced Performance • Improved Solution Quality • Risk Mitigation	• No enough time and resources to implement and test different types of algorithms on HPC • How to select results from different types of algorithms on HPC, in terms of objective or execution time? • Don't lose the way. Focus on our chosen algorithms. • Don’t give up, make our idea work!

Questions regarding the Algorithms

3. Did you/your team consider adjusting the parameters/heuristics of your algorithm based on network characteristics? If yes, explain how?

Answer: Yes.

Network Characteristics	Examples	Strategies
Size	• Small Networks: $N_B < 1500$ • Mid-Sized Networks: $1500 \le N_B < 6000$ • Large-Scale Networks: $6000 \le N_B < 20000$ • Ultra-Large Networks:$N_B \ge 20000$	• Regular or fast unit commitment • Number of iterations between UC, OPF, and contingencies. • Number of critical branches • Number of critical contingencies
Parameters	• $p_{max} - p_{min} \le 10^{-4}$ • $q_{max} - q_{min} \ge 1000$ • $r_{ij} \le 10^{-7}, x_{ij} \le 10^{-5}$	• Options for variable initialization for ACOPF • Parameters of the linear solver to enhance precision in solution

Questions regarding the Algorithms

4. Did you/your team try to use any machine learning approach to learn the Sandbox datasets?

Answer: Not use machine learning approaches.

Potential Benefits	Our Thoughts
• **Advanced Analytical Capabilities**: Machine learning could potentially uncover complex patterns and insights from the datasets. • **Predictive Power**: Machine learning models have the ability to predict outcomes based on historical data, which could be beneficial for forecasting and planning. • **Automation and Efficiency**: Employing machine learning could automate certain analytical processes, increasing overall efficiency.	• **Resource and Time Constraints:** Given the limited data resources, unpredictable networks for events, and firm project timeline, integrating machine learning was not a practical option for our team. The industry networks are even not released. • **Optimality and Feasibility of Results:** The results from machine learning models may not meet the high-performance standards set for our competition, given the precision required.

Questions regarding the Algorithms

5. Did you/your team consider changing the algorithmic approach/modeling approach when new datasets are published? If yes, why?

Answer:

Enhancements	Our Thoughts
• No major changes needed • Testing and correction for sure • Minor adjustments and refinements always	• Good experience and understanding on the potentials of the used algorithms. • Prepared for the large-scale networks, and fast solutions. • Flexible settings/options for the challenges from new datasets.

Questions regarding the Algorithms

6. Did the teams consider a "simultaneous multi-period" OPF approach (as opposed to considering each time period individually)? If so, how did it scale and what, if any, were the benefits to solution quality?

Answer: Not this time, but would like to test it in the future.

Potential Benefits	Our Thoughts
• **Enhanced Solution Quality through Holistic Optimization:** including inter-temporal constraints (e.g. ramping limit, energy limit)	• **Memory Limitation**: The extensive memory requirements for a simultaneous multi-period approach may exceed our available computational resources. • **Computational Complexity**: Handling multiple periods simultaneously adds significant complexity to the computation, increasing the risk of scalability issues. • **Optimality Issue**: More complicate/comprehensive model doesn't guarantee a more accurate result within a time limit, especially for the large case. However, it is still possible to try it using the parallel implementation of linear solver like PARDISO, especially for D2 and D3.

Questions regarding the Algorithms

7. How (if at all) did your team incorporate reserve constraints into the OPF subproblem(s)?

Answer:

Variable Elimination	Constraint Reduction
• Remove the variables that are fixed/constant. • Remove the intermediate variables.	• Reduce the quantity of zonal reserve constraints. • Merge the constraints.

Examples:

	Producing Device		Consuming Device	
Reserve Variables	On Status	Off Status	On Status	Off Status
p_j^{rgu}		×		×
p_j^{rgd}		×		×
p_j^{scr}		×		×
p_j^{nsc}	×		×	×
$p_j^{rru,on}$		×		×
$p_j^{rru,off}$	×		×	×
$p_j^{rrd,on}$		×		×
$p_j^{rrd,off}$	×	×	×	

Variable Removal

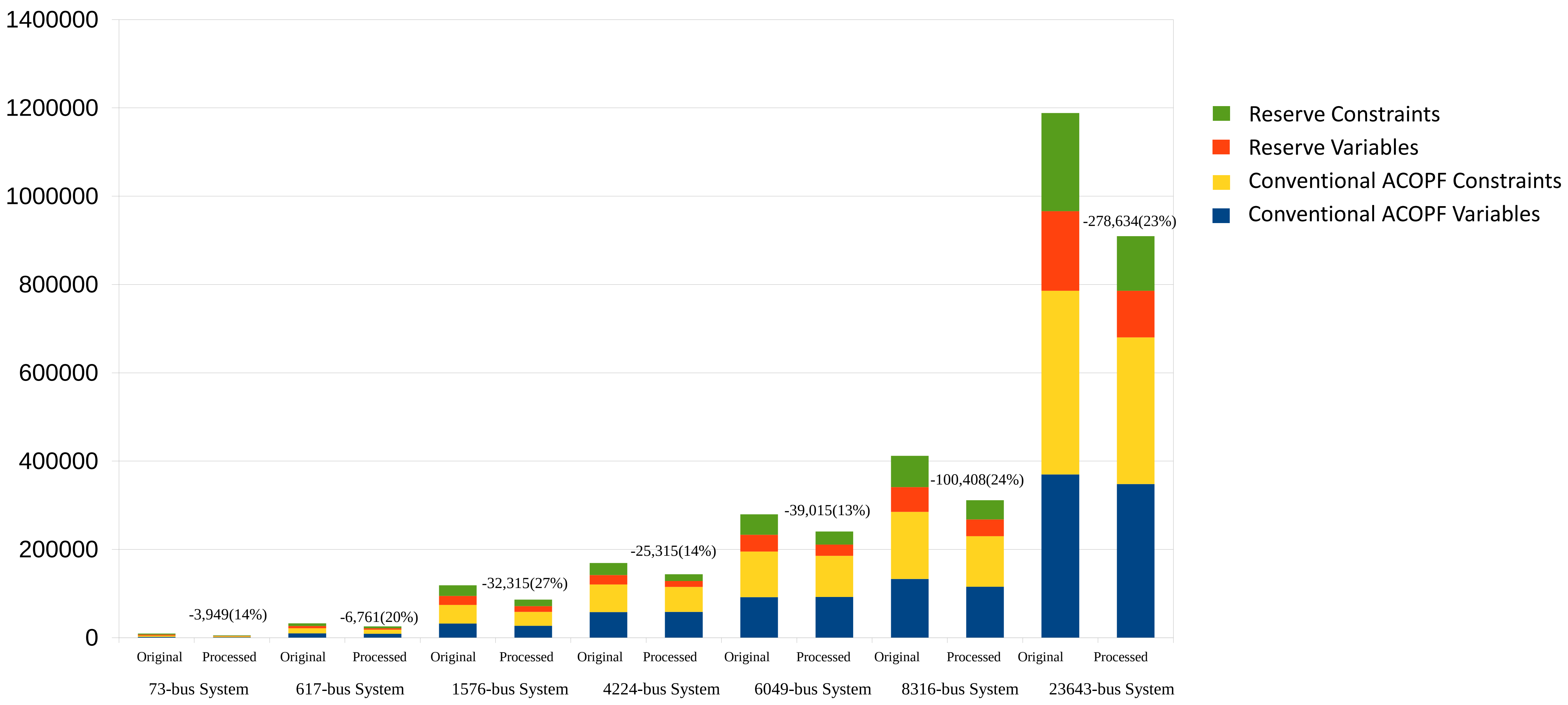
$$\sum_{j\in(G_n,D_n)}\left(p_j^{rgu}+p_j^{scr}\right)+p_n^{scr,+}\geq p_n^{scr,req}=\sigma_n^{scr}\max_{j\in G_n} p_j,\forall n\in N^p$$

$$\sum_{j\in(G_n,D_n)}\left(p_j^{rgu}+p_j^{scr}+p_j^{nsc}\right)+p_n^{nsc,+}\geq p_n^{nsc,req}=\sigma_n^{nsc}\max_{j\in G_n} p_j,\forall n\in N^p$$

Constraint Reduction

$$\sum_{j\in(G_n,D_n)}\left(p_j^{rgu}+p_j^{scr}\right)+p_n^{scr,+}\geq \sigma_n^{scr}p_j,\forall n\in N^p,j\in G_n^{Top}$$

$$\sum_{j\in(G_n,D_n)}\left(p_j^{rgu}+p_j^{scr}+p_j^{nsc}\right)+p_n^{nsc,+}\geq \sigma_n^{nsc}p_j,\forall n\in N^p,j\in G_n^{Top}$$


1400000
1200000
1000000
800000
600000
400000
200000
0
-3,949(14%)
-6,761(20%)
-32,315(27%)
-25,315(14%)
-39,015(13%)
-100,408(24%)
-278,634(23%)
Original
Processed
73-bus System
617-bus System
1576-bus System
4224-bus System
6049-bus System
8316-bus System
23643-bus System
Reserve Constraints
Reserve Variables
Conventional ACOPF Constraints
Conventional ACOPF Variables

Questions regarding the Algorithms

8. UC determines the binary variables and some continuous variables. We understand fixing the binary variables makes the remaining AC OPF a continuous nonconvex programming. How do you treat the decision of the continuous variables determined by UC?

Answer: Don't need the values of continuous variables determined by UC, except for the startup and shutdown power.

Yes. UC module will obtain the binary variables and some continuous variables. Only binary variables (e.g. device status), and the startup/shutdown power are fixed and provided to ACOPF module for determining other optimal continuous variables.

Basically, you need consider all device-level and system-level real/reactive power constraints (generation and reserve) to get a good/reasonable device status for ACOPF. How many constraints/what kinds of constraints you can cover in the UC module depends on the performance of the MILP solution engine (size, time, optimality, feasibility tolerance, ...).

Questions regarding the Algorithms

9. How do you update UC decisions if you find the first UC is not optimal or feasible?

Answer: Conduct iterations between UC decisions, ACOPF decisions, and even contingency analysis.

Mathematically speaking, the problem model is always "feasible" as it has slack variables for power mismatches and line violations. Thus, I would like to focus on the “optimal”.

For example, in case that ACOPF has any power mismatch/line violations, corresponding linear sensitivity-based violation constraints will be generated and added back to the UC module to update/adjust the device status. The iterations between UC and ACOPF will lead the solution to more optimal.

Usually, after a very few iterations, we can get a result with a "very small" bus power mismatch/line violation (assuming such solution exists).

Also, the linear sensitivity-based violation constraint we build is a kind of cut which can reflect the network issues/violations. In other words, you don't need to consider all network information/constraints in the UC model at the beginning. You can always find out the network issues/violations and add them in the further iterations.

Questions regarding the Grid Data

1. What were the 10 most difficult scenarios to solve? And why?

4. Did you notice considerable differences in difficulty amongst the networks?

Answer:

Network	Sample Scenarios	Reason of Difficulty
23643	C3E4N23643D1-S003-SW1 C3E4N23643D2-S003-SW1 C3E4N23643D3-S003-SW1	The substantial size of the system presents significant challenges not only for UC but also for ACOPF, particularly when faced with substantial zonal reserve penalties that necessitate the inclusion of reserve variables in the ACOPF formulation. It will be better to study this network if more testing scenarios can be released before final event.
1576	C3E3N01576D1-S027-SW1 C3E2N01576D2-S022-SW1	When faced with significant contingency penalties, achieving a top result requires the incorporation of contingency constraints and multiple iterations.
6717	C3E4N06717D1-S105-SW1	In certain scenarios, we encounter an ill-conditioned coefficient matrix, which requires a higher precision and solution quality of linear solver.
6708 (Industry)	C3E4N06708D1-S016-SW0/1 C3E4N06708D2-S023-SW1 C3E4N06708D3-S228-SW1	The range between the upper and lower bounds of the variables is beyond our expectation which affects the initial point of our ACOPF solver.
73	C3E4N00073D2-S991-SW0 C3E4N00073D2-S992-SW0 C3E4N00073D2-S996-SW0 C3E4N00073D2-S997-SW0	Usually not difficult. But, we get a significant penalty on bus power mismatches for certain scenarios (like 99*) where switching is prohibited.

Questions regarding the Grid Data

2. What were the 10 least difficult scenarios to solve? And why?

Answer:

Network	Sample Scenarios	Reason of Ease
73	C3E4N00073D1-S307-SW1 C3E4N00073D2-S303-SW1 C3E4N00073D3-S327-SW1	Small size. Easy to test. No special strategy needed.
617	C3E4N00617D1-S003-SW1 C3E4N00617D2-S014-SW1 C3E4N00617D3-S032-SW1	Small size. Typical network parameters. No special strategy needed.
2000	C3E4N02000D1-S033-SW1 C3E4N02000D2-S005-SW1 C3E4N02000D3-S007-SW1	Middle size, typical network parameters. No special strategy needed.
4224	C3E4N04224D1-S023-SW1 C3E4N04224D2-S023-SW1 C3E4N04224D3-S048-SW1	Middle – Large size. Didn't find any special issue for the scenarios of this network.
6049	C3E4N06049D1-S003-SW1 C3E4N06049D2-S015-SW1 C3E4N06049D3-S073-SW1	
8316	C3E4N08316D1-S203-SW1 C3E4N08316D2-S115-SW1 C3E4N08316D3-S311-SW1	

Questions regarding the Grid Data

3. Did you find difficulties with industrial networks (not released networks)? Explain why?

Answer: Yes.

We know nothing about the industrial networks. But, we can test it through Sandbox.

We start working on the industrial cases after we complete our code debugging and testing on other released networks, usually within the three days prior the submission deadline.

Very limited information from the evaluation log can help our testing on the industrial networks.

Questions regarding the Grid Data

5. Did you find any idiosyncrasies of specific grids?

6. Did you notice unusual behaviors/data in any grids?

Answer: Some data need be carefully processed in our algorithms. For example:

- Certain devices have an exceptionally narrow active power range, e.g. [0, 0.0001].
- The phase shifter range for transformers excludes 0.0 radians.
- Transformer tap ratios are set with a range that exclude the 1.0 value.
- For some devices, the output range of active/ reactive power is very broad, extending up to [0, 1500].
- The resistance (R) and reactance (X) values for certain transmission lines are notably minimal. e.g. 10^{-7}
- Penalty coefficients for zonal reserve power shortfalls are significantly high in certain 2000, 6049, 6717, and 24643-bus network scenarios. e.g. 5×10^5
- Penalty coefficients for branch violations could be very small or large in the network scenarios. e.g. 500 or 10^6
- High line shunt charging susceptance b in the certain scenarios of the network 73. e.g. 2.459 p.u.

Questions regarding the Grid Data

7. Which constraints were more challenging to satisfy?

Answer: Highlighted in red.

Hard Constraints	Soft Constraints
• Bus voltage limits • Device on-off status and related constraints • Producing and consuming devices: startup, shutdown, dispatchable power, ramping, reserve • Shunt real and reactive power constraints • DC branch flow limits	• Bus real and reactive power balance • Zonal reserve requirements • Producing and consuming devices: max/min energy over multiple intervals • AC branch flow limits • Post-contingency AC power flow limits

Questions regarding the Grid Data

8. How would you compare the computational complexity of larger grids with the small grids?

Answer:

Problem Complexity	Variety of Power Elements	Extreme Scenarios	Quantity of Variables, Constraints, and Contingencies	Optimal Solution	Amount of Resources Required	Execution Time
Small Grids	Less	Well designed	Small	Easy	Low	Fast
Larger Grids	More	More Practical	Huge	Difficult	High	Slow

Questions regarding the Grid Data

9. Regarding the data input format, is it easier to parse?

Answer:

Yes, the JSON format of the data simplifies parsing, as we leverage the Json-c library—a tool tailored for efficient JSON file manipulation in C. Our main focus is on diligent coding practices to avert any bugs that could result from typographical errors, ensuring the integrity and reliability of our data processing.

Answering Questions on Grid Data

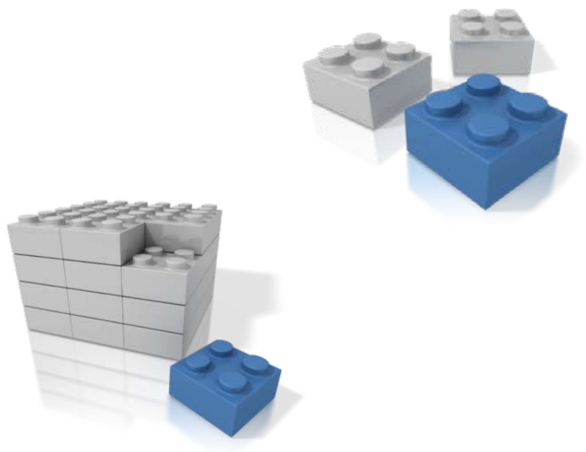
10. What are the main differences in the optimization behavior of D1, D2 and D3?

Answer:

Division	Optimization Priorities	Details
D1	Focus on **Speed**	The solution to the optimization problem must be obtained promptly. It is important that the algorithm delivers a solution within a constrained timeframe, rather than achieving an absolute best outcome.
D2&D3	Speed and Optimality **Balance**	The solution to the optimization problem should be achieved within a moderate timeframe. Our approach aims to deliver a solution that is both timely and of high quality, reflecting a balanced consideration of efficiency and effectiveness.

Concluding Remarks

- Enjoy DOE APAR-E GO Events (GO1, GO2, GO3 ….)
- Thanks GO3 administrative team and software sponsors
- Thanks my team members (Ms. Yehong Peng, Ms. Fasiha Zainab, Dr. Lin Gong)



References

- Y. Fu, Z. Li, and L. Wu, “Modeling and Solution of the Large-Scale Security-Constrained Unit Commitment,” *IEEE Transactions on Power Systems*, Vol. 28, No. 4, pp. 3524-3533, November 2013
- Y. Fu, M. Shahidehpour, and Z. Li, “Security-Constrained Unit Commitment with AC Constraints,” *IEEE Transactions on Power Systems*, Vol. 20, No. 3, pp. 1538-1550, August 2005
- Y. Fu, M. Shahidehpour, and Z. Li, “AC Contingency Dispatch based on Security-Constrained Unit Commitment,” *IEEE Transactions on Power Systems*, Vol. 21, No. 2, pp. 897-908, May 2006
- Y. Fu, and M. Shahidehpour, “Fast SCUC for the Large-scale Power Systems,” *IEEE Transactions on Power Systems,* Vol. 22, No. 4, pp. 2144-2151, November 2007
- A. Lotfjou, M. Shahidehpour, Y. Fu, and Z. Li, “Security-Constrained Unit Commitment with AC/ DC Transmission Systems,” *IEEE Transactions on Power Systems*, Vol. 25, No. 1, pp. 531-542, February 2010
- A. Kargarian, Y. Fu, and Z. Li “Distributed Security-Constrained Unit Commitment for Large- Scale Power Systems,” *IEEE Transactions on Power Systems*, Vol. 30, No. 4, pp. 1925-1936, July 2015
- C. Wang and Y. Fu, “Fully Parallel Stochastic Security-Constrained Unit Commitment,” *IEEE Transactions on Power Systems*, Vol. 31, No. 5, pp. 3561-3571, September 2016
- L. Gong, C. Wang, C. Zhang, and Y. Fu, “High-Performance Computing based Fully Parallel Security-Constrained Unit Commitment with Dispatchable Transmission Network,” *IEEE Transactions on Power Systems*, Vol. 34, No. 2, pp. 931 - 941, March 2019
- J. Guo, Y. Fu, Z. Li, and M. Shahidehpour, “A Direct Calculation of Line Outage Distribution Factors,” *IEEE Transactions on Power Systems*, Vol. 24, No. 3, pp. 1633-1634, August 2009
- C. Wang and Y. Fu, “A Distributed Calculation of Global Shift Factors Considering Information Privacy,” *IEEE Transactions on Power Systems*, Vol. 31, No. 5, pp. 4161-4162, September 2016
- M. Shahidehpour, W. F. Tinney, and Y. Fu, “Impact of Security on Power Systems Operation,” *Proceedings of the IEEE*, Vol. 93, No. 11, pp. 2013-2025, November 2005

THANK YOU!
ANY QUESTIONS …?

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