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SUGAR - Examples and Applications

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Overview

Demonstration of *what is possible* with SUGAR framework:

- **Unify steady-state simulation** of T&D networks
- Achieve **robust convergence to physical solution** for power flow and three-phase power flow problems
- **Localize and quantify** network power deficiencies
- Solve **billion+ size optimization problems**

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Power Flow for Extreme Events

- SUGAR's robust convergence **scales to any system size or complexity**
- Ex.: **Extreme contingency analysis** on the **Eastern Interconnection**
  - Converges from **any set of initial conditions** in SUGAR

Extreme Contingency Operation

Case	Contingency Type	No. of Buses	Standard Commercial Tool	SUGAR
			From initial solution or arbitrary initial conditions	
1	N-2	75456	X	✓
2	N-2	78021	X	✓
3	N-3	80293	X	✓
4	N-3	81238	X	✓

✓ converged X diverged

Robust Three-Phase Power Flow

- Robust convergence is extended to three-phase networks as well

Cases	#Nodes	SUGAR	Standard Tool
R1-12.47-1	2455	✓	✓
R3-12.47-3	7096	✓	✓
Network Model 1	1420	✓	✓
Case145*	176	✓	X
Case9241pegase*	12528	✓	X

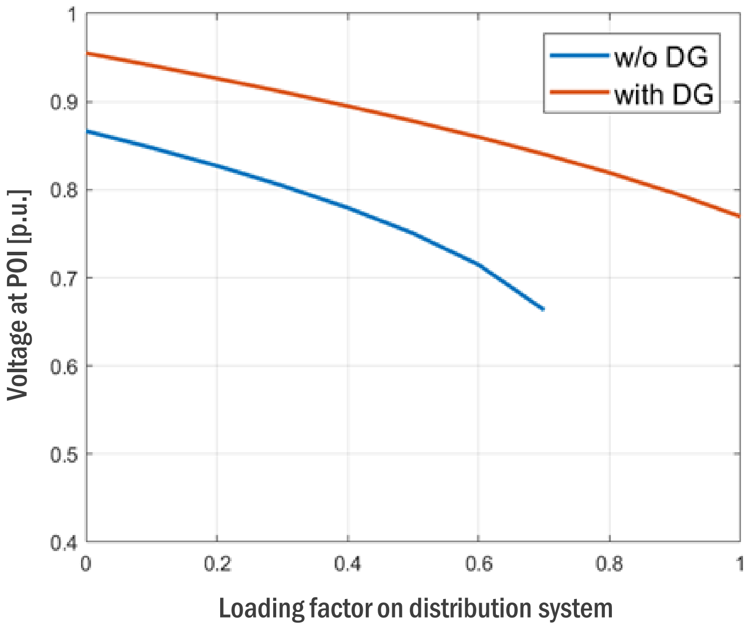
* Transmission networks were extended to three-phase models

✓ converged
X diverged

- Standard three-phase tools do not always converge
  - Especially true for **networks with significant generation**
  - **Circuit simulation methods** enable convergence for hard to solve three-phase test cases

Combined Transmission and Distribution Analysis

- Design and evaluation of combined T&D models increasingly critical due to growing **generation in the distribution grid**
  - Study the **impact of distribution on transmission** and vice-versa

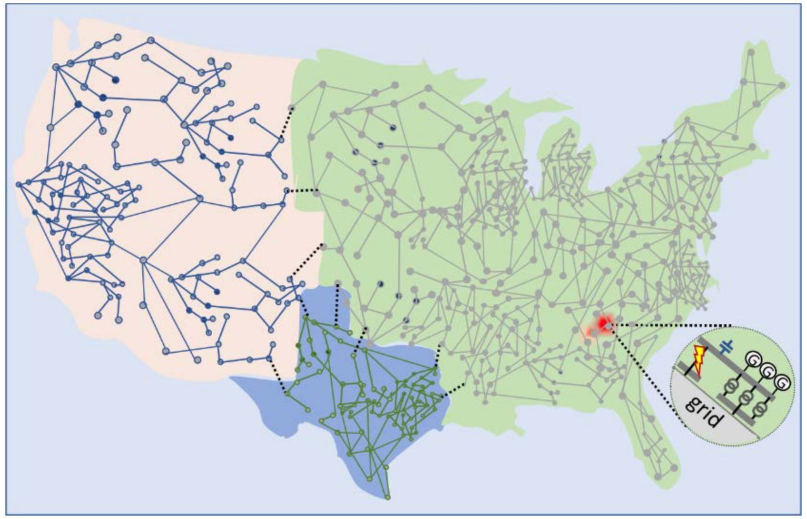


Ex.: 80k+ node Eastern Interconnection with an 8k+ node three-phase distribution network
- Evaluate impact of distributed generation (DG) on transmission voltages

A. Pandey and L. Pileggi, "Steady-State Simulation for Combined Transmission and Distribution Systems," in *IEEE Transactions on Smart Grid*. Early Access.

Optimal Siting of Grid Resources

- Ex.: An N-1 contingency on a Synthetic USA transmission network[1]
  - SUGAR **localizes and quantifies** the area with power deficiency (commercial tools do not converge)
  - **Corrective action with capacitor bank** makes the case feasible
- To **optimally site equipment**, develop optimization framework to locate resources while solving NERC mandated contingencies

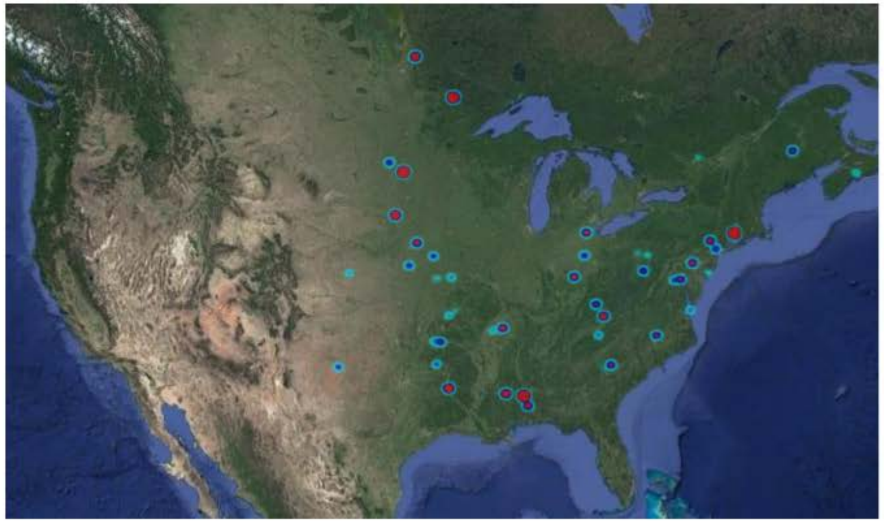


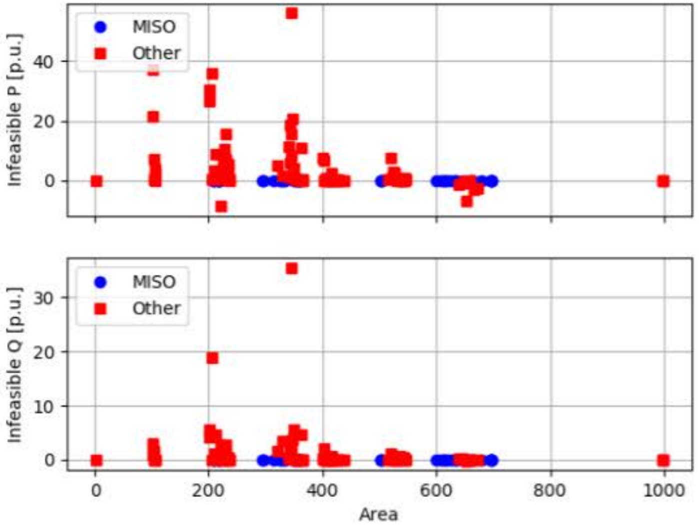
Localized area of infeasibility within the Synthetic USA network

1. A. B. Birchfield, et.al., "Power Flow Convergence and Reactive Power Planning in Creation of Large Synthetic Grids", IEEE Trans. on Power Systems, 2018.

ISO Study - High Renewable Penetration

- Ex.: High renewable penetration policy study on U.S. Eastern Interconnect
  - Initial case created by replacing conventional generation with renewables, scaling loads
  - Power flow solution indicates and quantifies infeasible power
  - Use SUGAR to re-dispatch resources to get a feasible working case

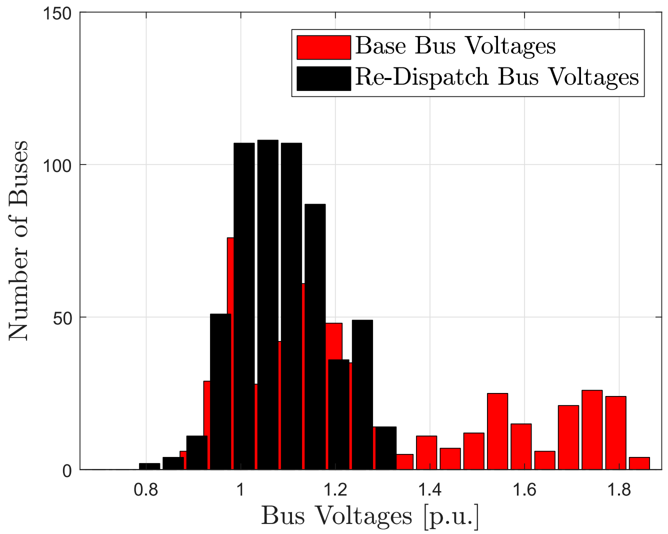




https://www.ferc.gov/CalendarFiles/20190626081630-4%20-%20FERC_MISO_PST1.pdf

Reliability Study for Nigerian Grid

- Ex:. An un-dispatchable network received from a Nigerian utility
  - The network had extreme voltages upon convergence
  - Can soft technological improvements improve the grid voltages?
- Optimization framework **improves network reliability[1] without capital investment**
  - Recommended generator voltage set-points **improved voltage profile**
- Extend framework to develop **actionable recommendations**
  - Evaluate decision against critical contingencies, loading scenarios and utility decision variables

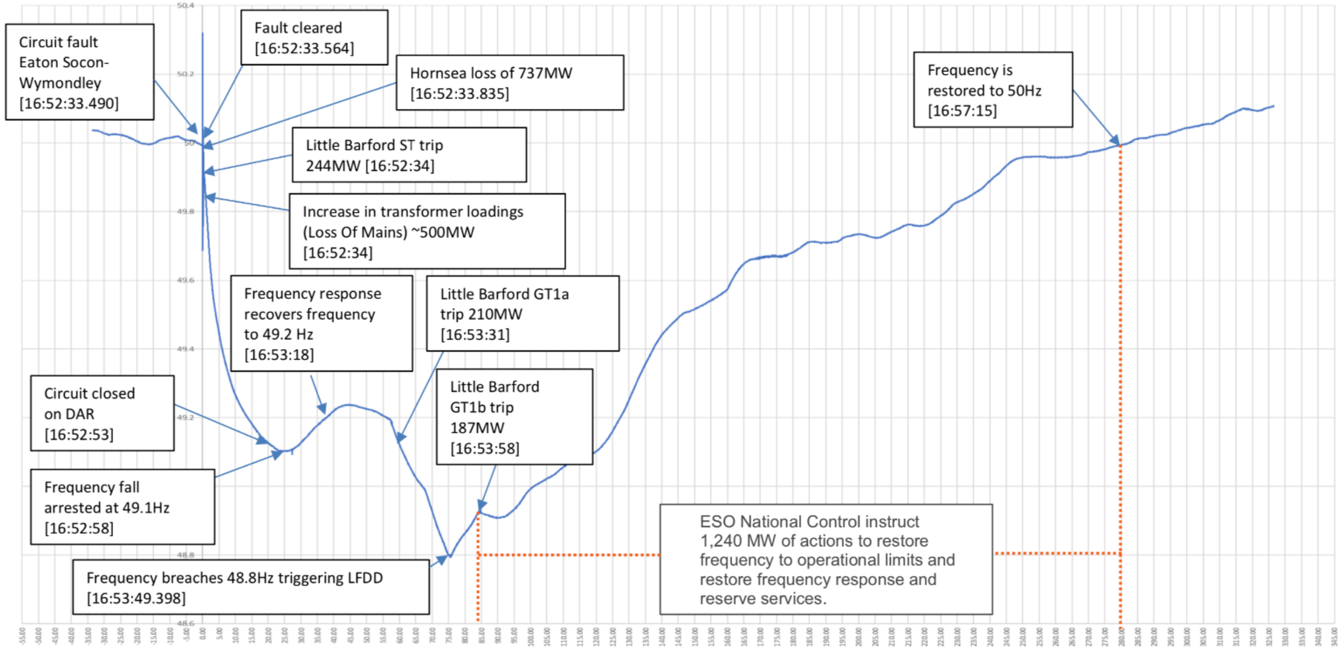


Bus voltages for a Nigerian grid planning case

1. A. Pandey et al, "Improving Voltage Profile of the Nigerian Power Grid," in Proc. IEEE PES/IAS PowerAfrica Conference, Abuja, Nigeria, August 2019.

Modeling Frequency in Power Flow

- Commercial power flow tools generally do not capture frequency in steady-state
  - Useful for studying events such as controlled blackout in UK[1]



1. National Grid ESO, "Interim Report into the Low Frequency Demand Disconnection (LFDD) following Generator Trips and Frequency Excursion on 9 Aug 2019," August 16,2019

Simulating Cascading Outage

- Simulating cascading outages can avoid or mitigate such events
  - Differentiate system **blackout from simulation divergence**
  - Model frequency behavior to **better mimic reality**
- Applied N-2 contingency event to a stable 8k+ bus network
  - Cascading event led to system blackout

Initiating Event ⇨ Cascade Stage 1 ⇨ Cascade Stage 2 ⇨ Cascade Stage 3 ⇨ SYSTEM BLACKOUT

Initiating Event:
<u>N-2 contingency</u>
Branch: 5408-5702*
Branch: 5408-5687*

* Circuit 1
** Circuit 2

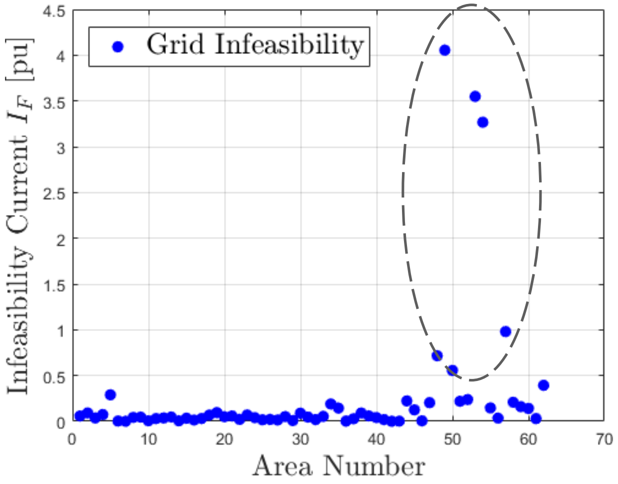
Cascade Stage 1:
<u>Devices Tripped</u>
Branch: 4081-7052
Branch: 5408-5702**
Generator: 7773

<u>Island 1: Feasible</u>
$I_{F1} = 0$
$\Delta f_1 = -0.026$ Hz

Cascade Stage 2:
<u>Devices Tripped</u>
Branch: 2228-5687
Branch: 5408-5687**
Branch: 5408-10000

1 New Island Created
<u>Island 1: Feasible</u>
$I_{F1} = 0$
$\Delta f_1 = -0.025$ Hz
<u>Island 2: Infeasible</u>
$f_2 < 58$ Hz

Cascade Stage 3:
2 New Islands Created
<u>Island 1: Infeasible:</u>
$I_{F1} = 0.533$ pu
$\Delta f_1 =$ -0.016 Hz
<u>Island 2:Infeasible</u>
$f_2 < 58$ Hz
<u>Island 3: Infeasible</u>
$f_3 < 58$ Hz
<u>Island 4: Infeasible</u>
$f_4 < 58$ Hz



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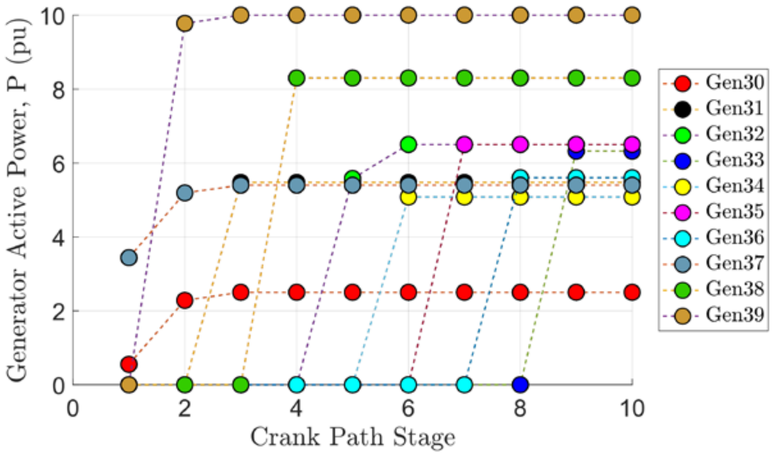
Grid Restoration with Compromised SCADA

- Robust grid restoration under comprised SCADA (e.g. during cyber-attacks) an unsolved problem
  - Build and maintain local models; update with local measurements in real-time
- Optimize for restoration sequence in real-time
  - Prevent tripping of protective devices; include frequency-based schemes



Generator restoration sequence for IEEE 39 bus network

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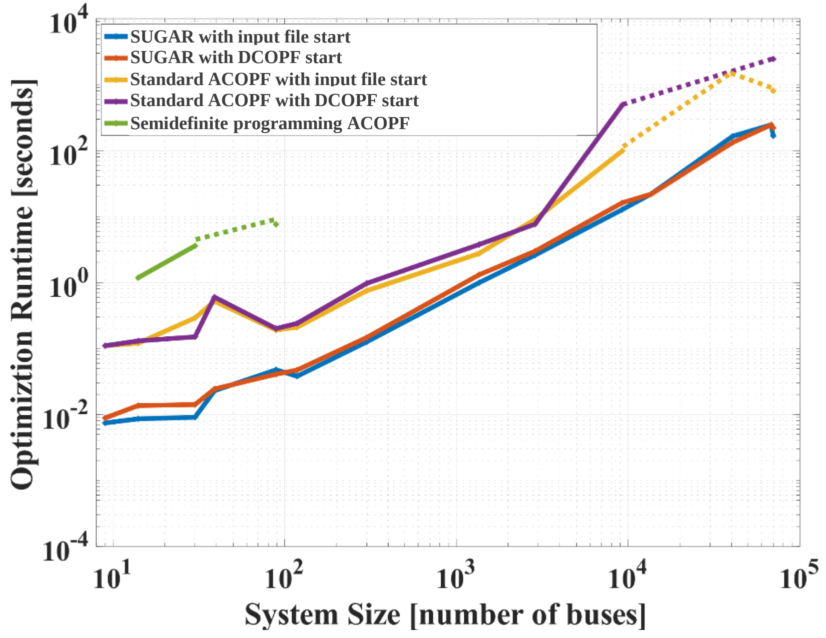
Robust AC-OPF Analysis

- SUGAR robustly solves **AC-OPF circuit** to find an optimal solution[1]
- Circuit framework for optimization **enables efficient parallelism**
  - Critical for N-x Security Constrained AC Optimal Power Flow (SCOPF) problem

Runtime comparison for optimized networks



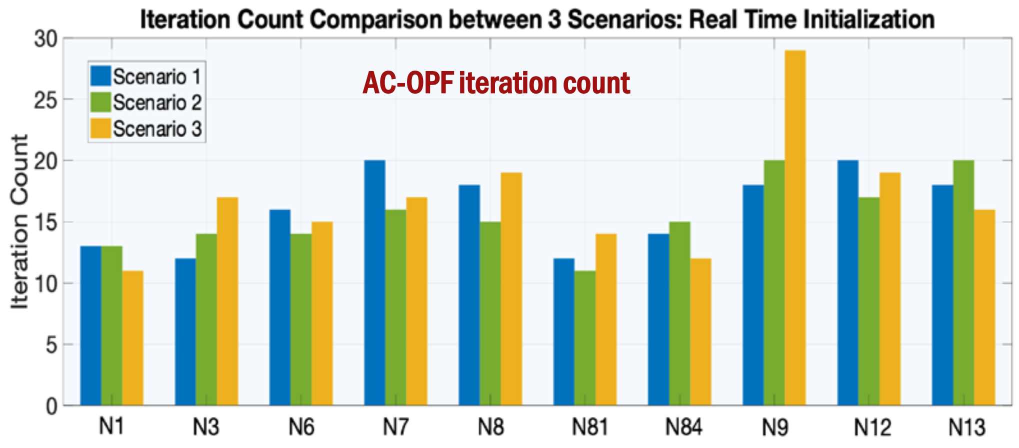
Test Case	SUGAR	MATPOWER with 'MIPS/FMINCON'
	Cost [$/hr]	Cost [$/hr]
Case 1354	74,064.30	74,064.30
Case 2869	133,993.48	133,993.48
Case 9241	315,902.49	315,903.36
Case 13659	386,106.58	---
Case 40605	15,395,681.29	---
Case 68251	27,551,688.77	---

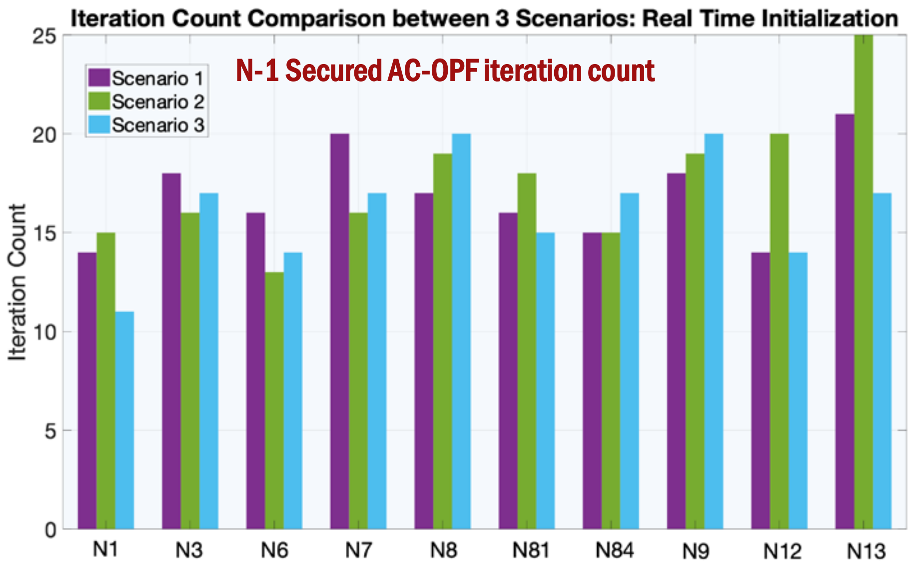
1. M. Jereminov, A. Pandey and L. Pileggi, "Equivalent Circuit Formulation for Solving AC Optimal Power Flow," in *IEEE Transactions on Power Systems*, vol. 34, no. 3, pp. 2354-2365, May 2019.

N-1 Secured AC Optimal Power Flow Results*

- **Iteration count** bounded by **network complexity not problem size**
- With efficient distributed matrix solver and circuit heuristics, SUGAR is **scalable to realistic SC-OPF problems**

ARPA-E GO Competition Test Cases





*Solved within minutes on a SUGAR cloud platform, courtesy of Pearl Street Technologies

SUGAR – ARPA-E Grid Optimization Challenge

- SUGAR is a leading contender in ARPA-E Grid Optimization Challenge
  - Largest problem size with **hundreds of millions of variables**
  - Competition based on synthetic networks, but the framework developed for real grids
- Extending the approach to an **industry acceptable solution** is a key goal

Trial Event 2
- Code2 Time Limit
- Code2 Open Source

Leaderboards
- Trial Event 1 Leaderboard
- Trial Event 2 Leaderboard
- Trial Event 3 Leaderboard

TRIAL EVENT 3 - DIVISION 1

updated 10/1/2019

Team Name	Team Leader	Leader's Organization	Team Members	Score
GMI-GO	Prof. Xu Sun	Georgia Institute of Technology	Santanu Dey Amin Gholami Xu (Andy) Sun Kaizhao Sun Shixuan Zhang	1,595,939.67
Pearl Street Technologies	Dr. Hui Zheng	Pearl Street Technologies	David Bromberg Marko Jereminov Amritanshu Pandey Larry Pileggi Hui Zheng	1,660,477.42
BAT	Mr. Andrew George Telyatnik	Individual	Andrew Telyatnik	2,232,640.14

ARPA-E GO Competition

Future Challenges

Robust analysis of grid of tomorrow requires:

- **Generic optimization framework** that is robust and scalable, capable of running on distributed cores (servers or cloud)
- **Distributed analysis** of networks while utilizing localized measurement data including those from internet of things (IOTs)
- **Newer more complex models** to map behavior of new-age power electronics-based grid devices and control

Contributors to Presentation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