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TECHNOLOGIES OFFICE
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Advanced Grid Research
OFFICE OF ELECTRICITY
US DEPARTMENT OF ENERGY

Grid Optimization with Solar (GO-Solar)

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HECO Contributors:	Marc Asano, Alan Hirayama, Wei-Hann Chen

ADMS Test Bed Webinar
February 16, 2022

NREL/PR-5D00-82026

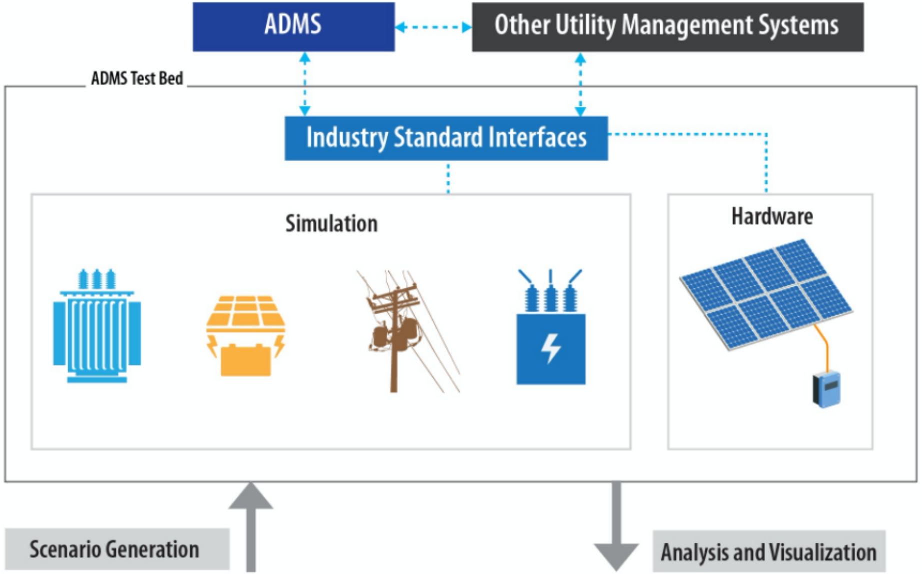
Advanced Distribution Management System (ADMS) Test Bed

Goal: Accelerate industry adoption of ADMS to:

- Improve normal operations with high DERs
- Improve resilience and reliability.

Approach: Partner with utilities and vendors to evaluate specific use cases and applications.

- Set up a realistic laboratory environment:
  - Simulate real distribution systems
  - Integrate distribution system hardware
  - Use industry-standard communications
  - Create advanced visualization capability.



https://www.nrel.gov/grid/advanced-distribution-management.html

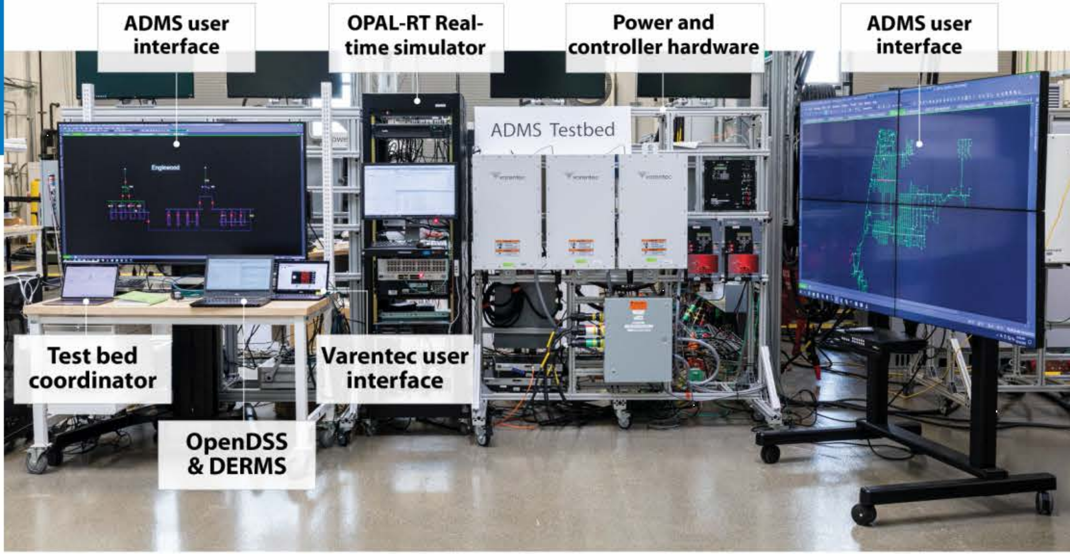
ADMS Test Bed

Expected outcomes: Increased industry confidence in ADMS technology through:

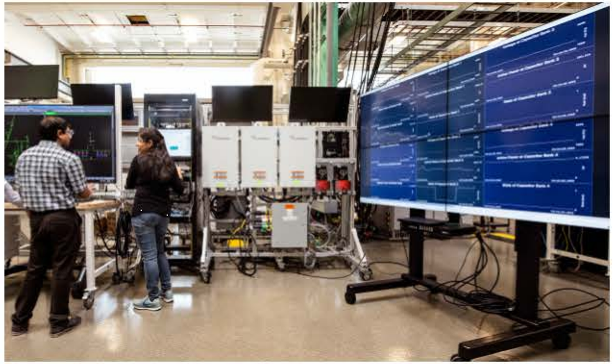
  - Laboratory demonstration of applications for specific use cases
  - Analysis and potential application to other utilities.

Progress:

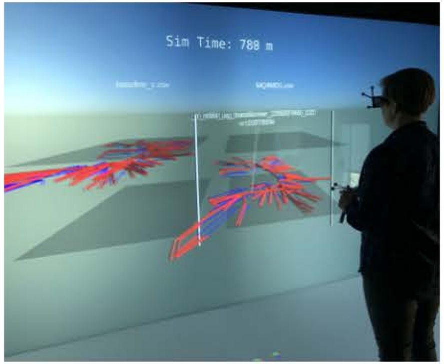
- ADMS test bed capabilities developed:
  - Multi-timescale cosimulation using HELICS (OpenDSS/Opal-RT/RTDS)
  - Hardware integration
  - Communications interfaces
  - Data collection and visualization.
- Seven conference papers published/accepted.



Photos by NREL



2D real-time visualization



3D visualization

Future Events

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ADMS Test Bed Webinars:

- SOLAR EXPERT, March 15, 2022
- FLISR in the Presence of DERs, May 5, 2022
- Distribution DER provide bulk services, June 9, 2022

IEEE Smart Grid webinar: March 28, 2022

ADMS test bed workshop: *planned for in-person at NREL*

We had set a tentative date of April 19-20, 2022

→ *Need to postpone (again) due to ongoing Covid restrictions*

→ *October/November timeframe*

NREL ESIF Retweeted

NREL
@NREL

A recent @ESIFLabs workshop showcased our advanced distribution management system (ADMS) test bed, which helps utilities evaluate their ability to monitor and coordinate #AdvancedEnergy assets for a more efficient and secure #grid. Learn more about it at bit.ly/2M0m3pe

Jan 10, 2020

NREL ESIF
@ESIFlabs

A recent @NREL workshop demonstrated our advanced distribution management system (ADMS) test bed, which allows a utility to evaluate performance of ADMS applications on their current and envisioned future system at a lower cost and no risk to customers. bit.ly/2r6mfMm

1:56 PM · Dec 5, 2019 · Twitter Web App

ADMS Test Bed Use Cases

Completed:

- Peak load management with ADMS and DERMS
    - Holy Cross Energy/Survalent
- ADMS network model quality impact on VVO
    - Xcel Energy/Schneider Electric
- AMI-based, data-centric grid operations
    - SDG&E + GridAPPS-D

Active:

- FLISR in the presence of DERs (April 2022)
    - Central Georgia EMC/Survalent
- T&D: Distribution DER provide bulk services (May 2022)
    - Xcel Energy + GridAPPS-D → May 2022
- Federated DERMS for high PV system (August 2022)
    - Southern Company/Oracle + GridAPPS-D

ADMS test bed capabilities used by:

Completed:

- Non-wires alternatives HCE HIP
- ECO-IDEA, GO-SOLAR, SolarExpert

Active:

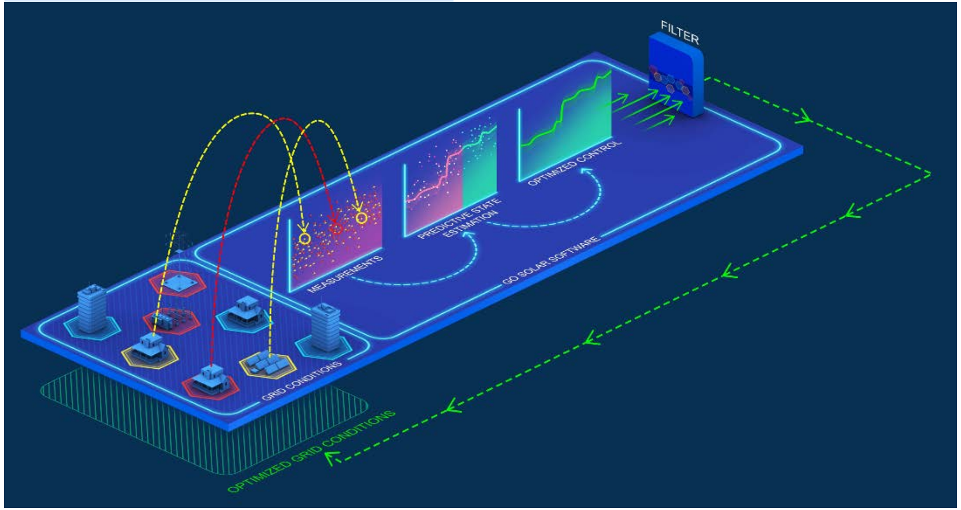
- FAST-DERMS (Feb 2023)
    - SDG&E, Oracle, EPRI + GridAPPS-D
- RONM (Dec 2022)
    - SDG&E, Cobb EMC
- REORG (Mar 2024)
    - Holy Cross Energy, Minsait ACS
- PIVA (Sep 2024)
    - GridBright, SDG&E, Oracle
- DynaGrid (Dec 2024)
    - DTE Energy

Project Objectives

Challenge #1:
Operations with extreme penetrations of distributed PV

Challenge #2:
Communicate and control with millions of DERs

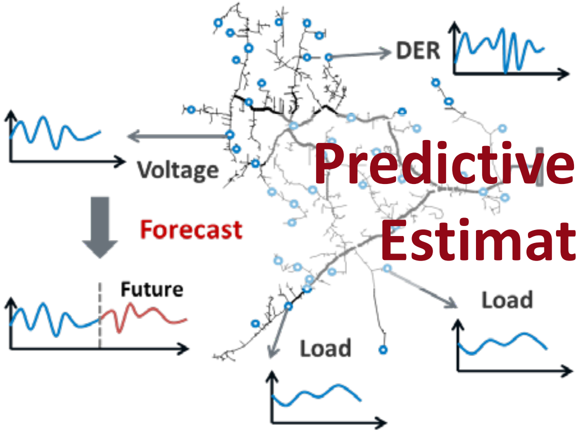
GO-Solar Solution



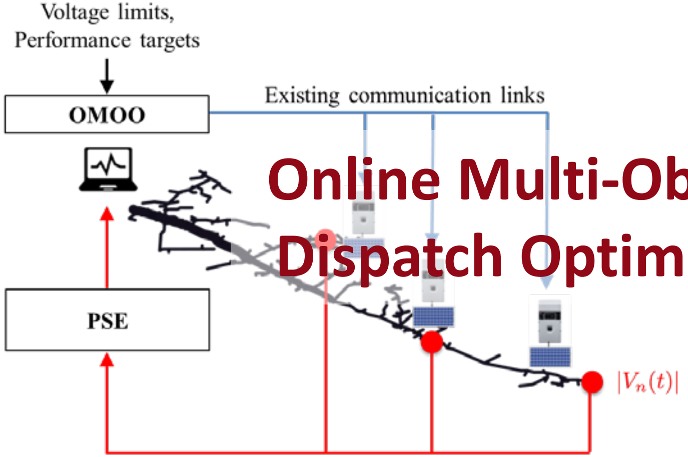
Manage **extreme penetrations of solar** and other DERs **using only a few measurement points** through matrix completion and multi-kernel learning-based **predictive state estimation (PSE)** **and only a few control nodes** dispatched through dual timescale **online multi-objective optimization (OMOO)** using voltage-load sensitivities to guide fast feedback response

GO-Solar Key Activities

Algorithms

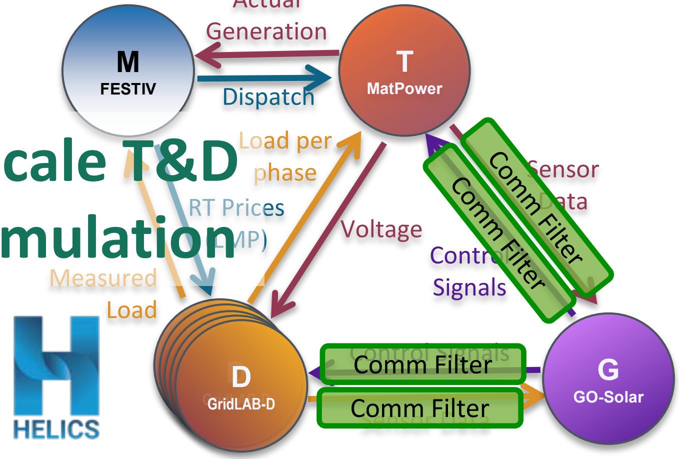


Predictive State Estimation

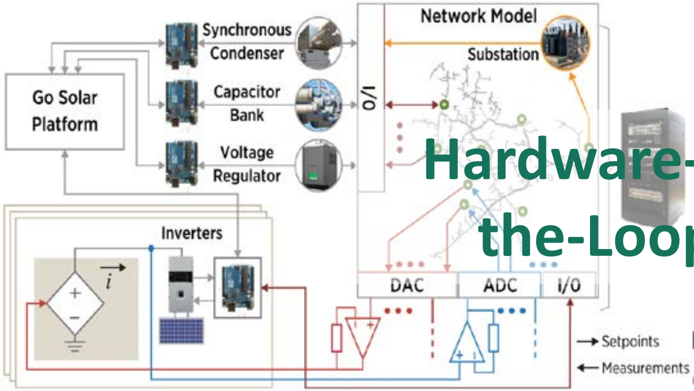


Online Multi-Objective Dispatch Optimization

Validation



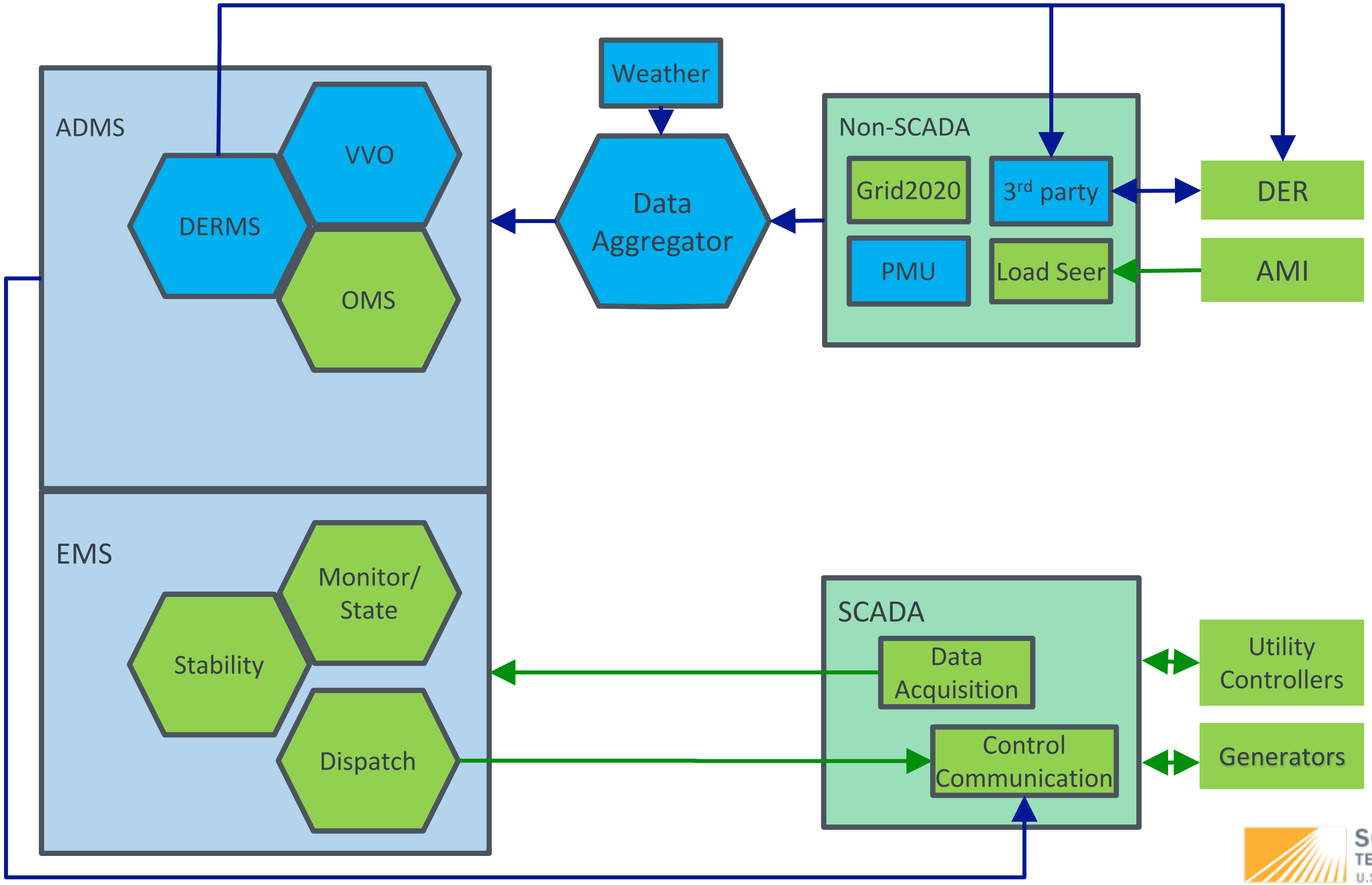
Full-scale T&D Co-Simulation



Hardware-in-the-Loop

GO-Solar Interface with Enterprise Systems

2030 Expected



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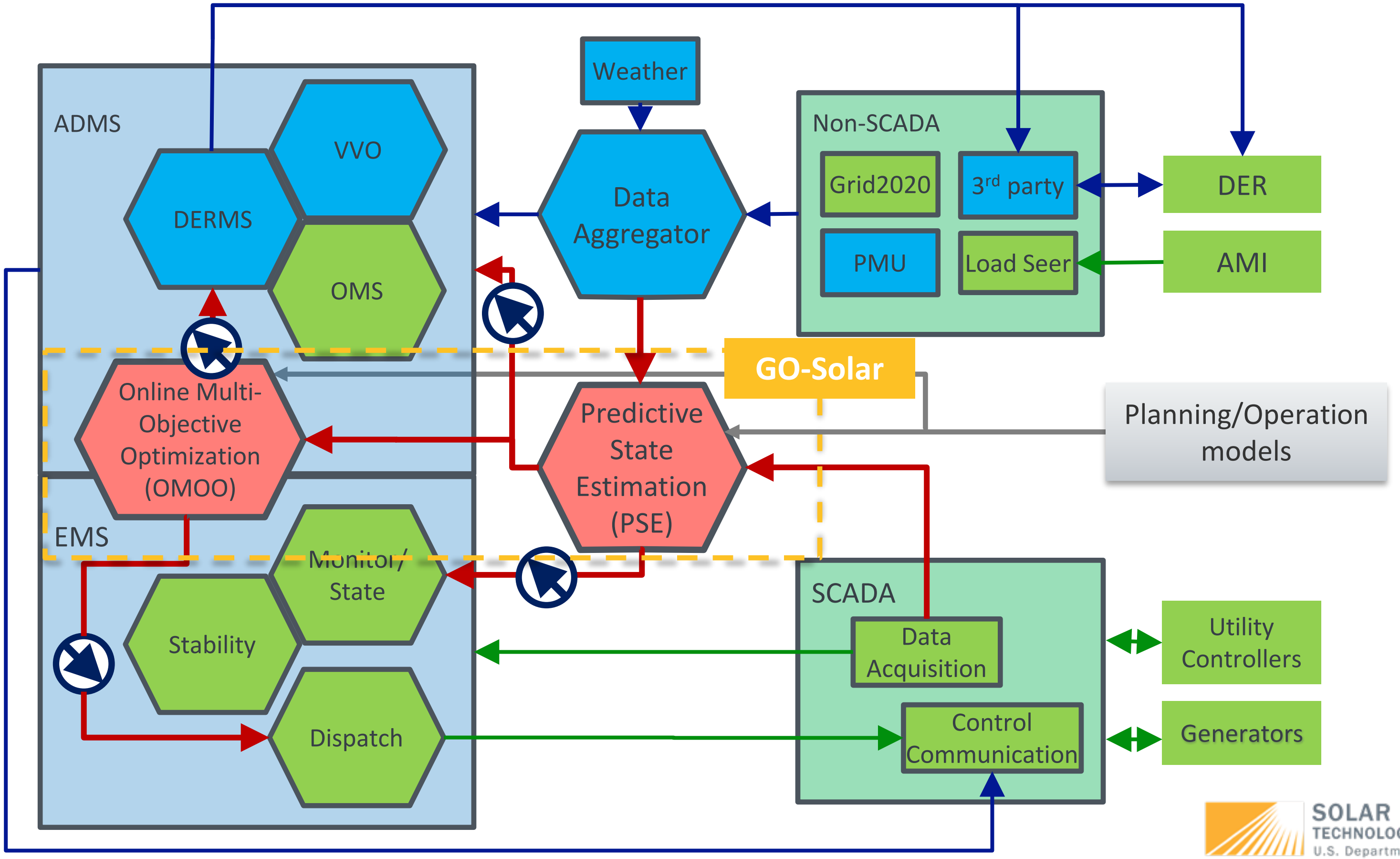
GO-Solar Interface with Enterprise Systems

With GO-Solar



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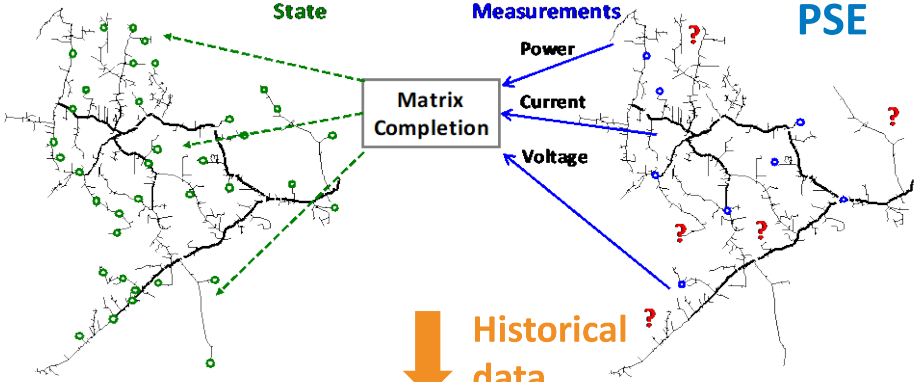
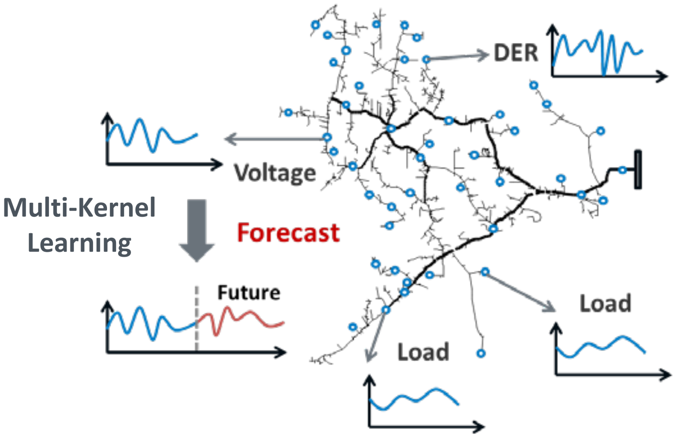
GO-Solar Technology

Integrated GO-Solar Platform

PSE



Historical data



Forecasted voltages

OMOO

Optimal set points

Fast (every Y seconds)

- Uses online optimization to follow the optimal trajectory
- Adjusts the set points of DERs in real time

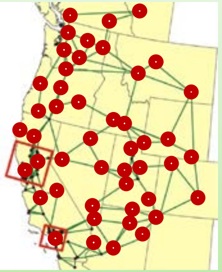
Planned set points

Slow (every X minutes)

- Solves OPF to mitigate potential voltage violations
- Provides nominal setpoints for DERs and legacy devices

Matrix Completion for State Estimation

vs. Conventional state estimation



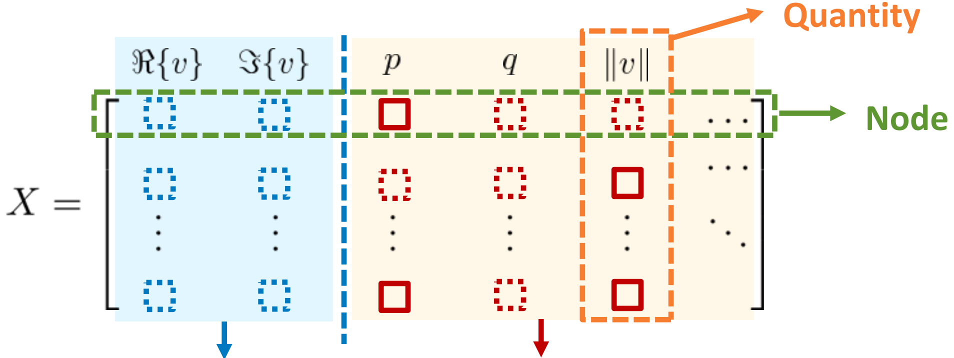
- Weighted least squares
- Objective: Minimize the weighted residuals

Requires redundant measurements

Concept:

Netflix Recommendation System

+ Power Systems Constraints (linearized) [1]-[3]



Unknown ← **State variables** **Measurements** → **Partially known**

Key idea: Estimate unknown elements using correlation

Objective function $\boxed{\min \textbf{(Rank of matrix } X \textbf{)}}$ **New**

Constraints **Known elements in** X **= Measurements**

(2-point Linearized) power flow equations

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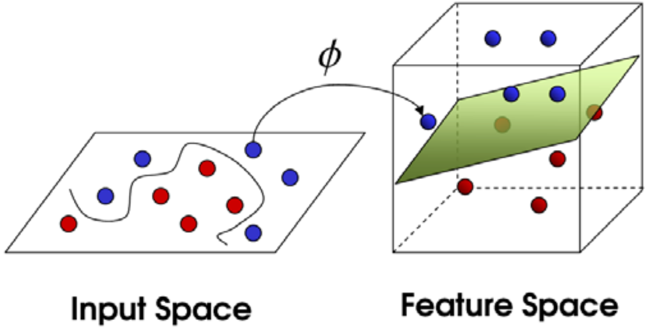
[1] Y. Zhang, A. Bernstein, A. Schmitt, and R. Yang, "State Estimation in Low-Observable Distribution Systems Using Matrix Completion," *HICSS-52 conference*, 2019.
[2] P. Donti, Y. Liu, A. Schmitt, A. Bernstein, R. Yang, and Y. Zhang, "Matrix Completion for Low-Observability Voltage Estimation," in *IEEE Transactions on Smart Grid*, vol. 11, no. 3, pp. 2520-2530, May 2020.
[3] Y. Liu, A. Sagan, A. Bernstein, R. Yang, X. Zhou, and Y. Zhang, "Matrix Completion Using Alternating Minimization for Distribution System State Estimation," *IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids*, Tempe AZ, October 6-9, 2020.

Multi-Kernel Learning for State Forecasting

Goal: Learn the spatiotemporal correlation between measurements and system states

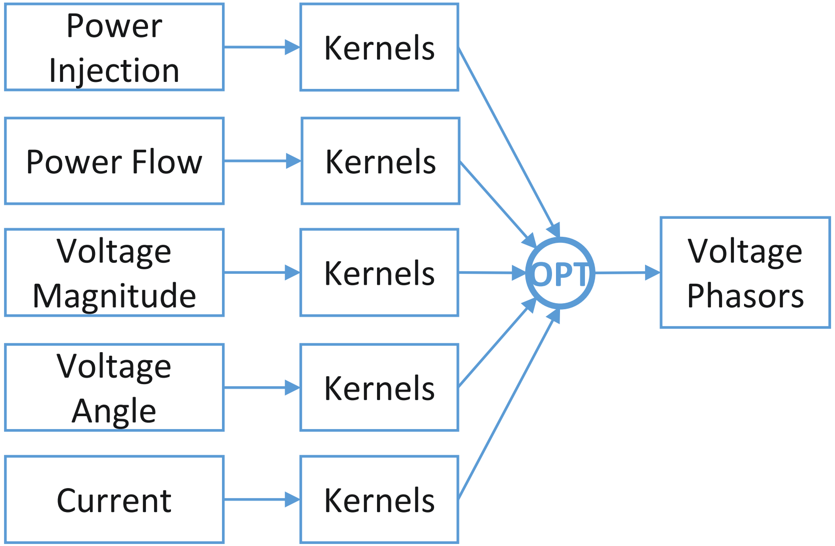
Kernel Learning Concept

- Use kernel functions to map the input space to a higher-dimension feature space
- Learn the relationship in the feature space



Source: *R. G. Esfahani and A. A. Mohammad, "Towards an anomaly detection technique for web services based on kernel methods," IEEE Innovations in Information Technology, 2009.*

Expanding to Multi-Kernel Learning



Measurements **Kernels** **System States**

Slow-Scale OMOO: VLSM-based Optimization

- **Voltage-Load Sensitivity Matrix (VLSM)** based mixed-integer linear problem [6]
  - Can handle integer constraints for taps/caps

Step 1: Build VLSM (periodically)

$$|\delta V| = |VLSM_P||\delta P| + |VLSM_Q||\delta Q|$$

$$\left|\begin{matrix} \delta V_1 \\ \delta V_2 \\ \vdots \\ \delta V_n \end{matrix}\right| = \left|\begin{matrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & \ddots & & p_{2n} \\ \vdots & & \ddots & \\ p_{n1} & p_{n2} & & p_{nn} \end{matrix}\right| \left|\begin{matrix} \delta P_1 \\ \delta P_2 \\ \vdots \\ \delta P_n \end{matrix}\right| + \left|\begin{matrix} q_{11} & q_{12} & \cdots & q_{1n} \\ q_{21} & \ddots & & q_{2n} \\ \vdots & & \ddots & \\ q_{n1} & q_{n2} & & q_{nn} \end{matrix}\right| \left|\begin{matrix} \delta Q_1 \\ \delta Q_2 \\ \vdots \\ \delta Q_n \end{matrix}\right|$$

Step 2: Solve MILP (minutes)

$$Min\ Z = \omega_1 \xi C + \omega_2 \Delta V + \omega_3 M_{reg}$$

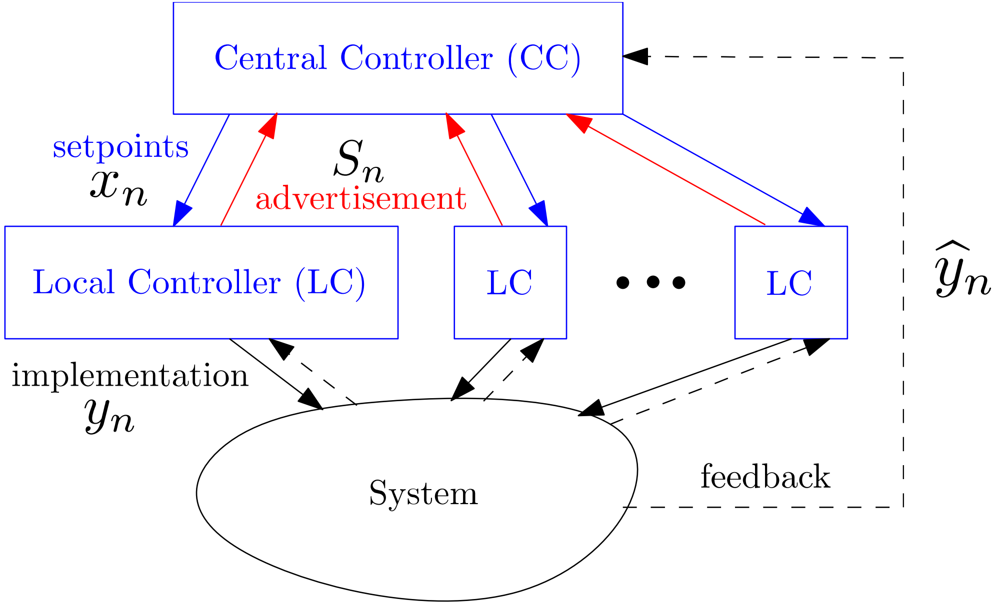
$$\begin{aligned} C &= \lambda_{Load} \sum_{i=1}^{n} \left(P_{control}^{Load}(i)\right)^2 + \lambda_{PV}^{P} \sum_{i=1}^{n} \left(P_{control}^{PV}(i)\right)^2 + \lambda_{PV}^{Q} \sum_{i=1}^{n} \left(Q_{control}^{PV}(i)\right)^2 \\ &+ \lambda_{ES}^{Q} \sum_{i=1}^{n} \left(P_{control}^{ES}(i)\right)^2 + \lambda_{cap} \sum_{i=1}^{n} \left(s(i) Q_{cap}(i)\right)^2 \\ &+ \lambda_{reg} \sum_{t=1}^{n_{reg}} \left(M_{Tap}(t) - M_{Tap}^{0}(t)\right)^2 \end{aligned}$$

Output: Dispatch/set points for DERs and utility legacy devices

[6] X. Zhu and Y. Zhang, "Coordinative Voltage Control Strategy with Multiple-Resource for Distribution Systems of High PV Penetration," *World Conference on Photovoltaic Energy Conversion (WCPEC-7)*, Waikoloa, Hawaii, June 10-15, 2018.

Fast-Scale OMOO: Online Optimization

- Goal: Follow OPF trajectory
- Key ideas [7]:
  - Hierarchical control
  - Lots of math with provable bounds
  - Single-step gradient
    - Rather than converging at each timestep, loosely converge across fast time steps



Output: Adjusted DER setpoints in real time

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[7] A. Bernstein and E. Dall'Anese, "Bi-Level Dynamic Optimization with Feedback," *the 5th IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, Montreal, Quebec, Canada, Nov. 2017.

Voltage Estimation

- Different sensors
  - Substation SCADA: P, Q, |V|, θ
  - Grid 2020: P, Q, |V|
  - AMI: P, |V|

HECO Feeders

2576 nodes

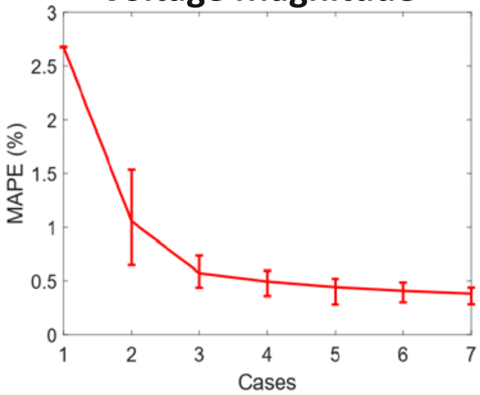
535 nodes w/ loads

100% PV penetration

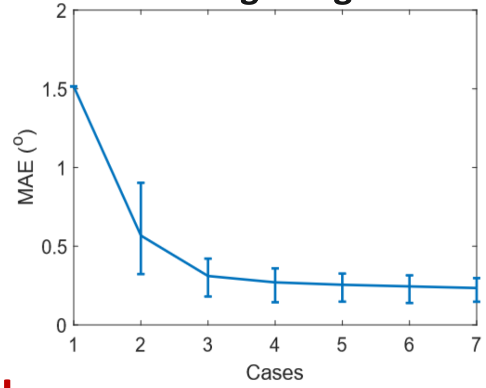
- Realistic scenarios

Case	1	2	3	4	5	6	7
0 Inj.	√	√	√	√	√	√	√
Sub.	√	√	√	√	√	√	√
Grid 2020	X	1%	1%	1%	1%	1%	1%
AMI	X	X	1%	2%	3%	4%	5%

Voltage Magnitude



Voltage Angle



Accurate state estimation with Sub. + 1% Grid 2020 + 1% AMI

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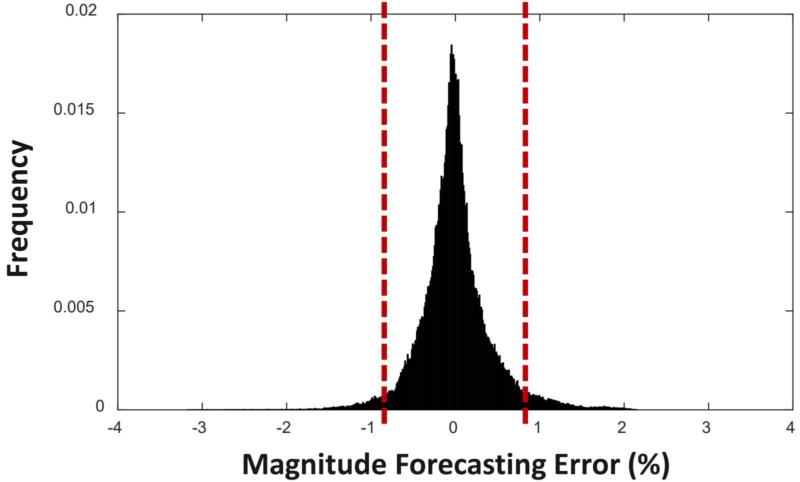
Voltage Forecasting

- 15-minute-ahead @ 1-minute resolution
- Input: P and Q at load nodes for the past 1 hour
- Training: 1-minute power flow results for 3 days (sliding window)

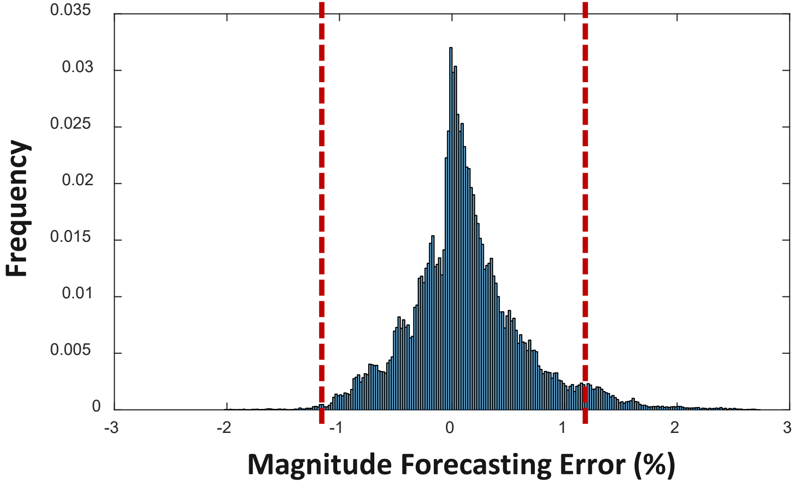
Training

95% CI: ±0.91%



Testing (1/5 of data)

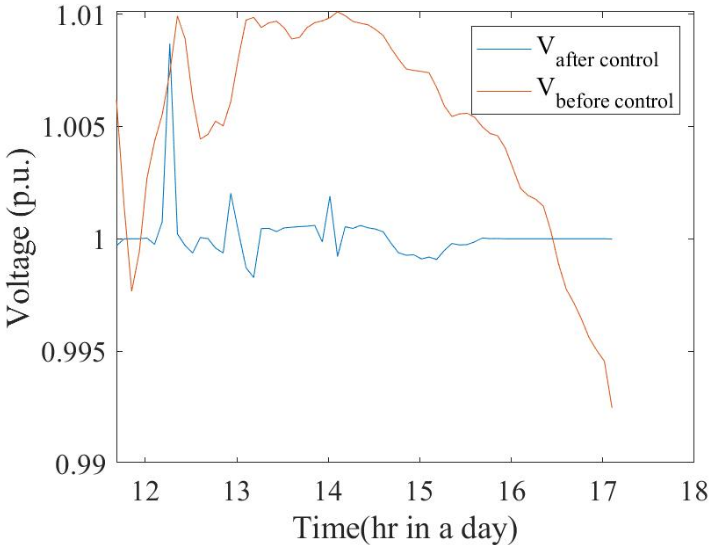
95% CI: ±1.13%



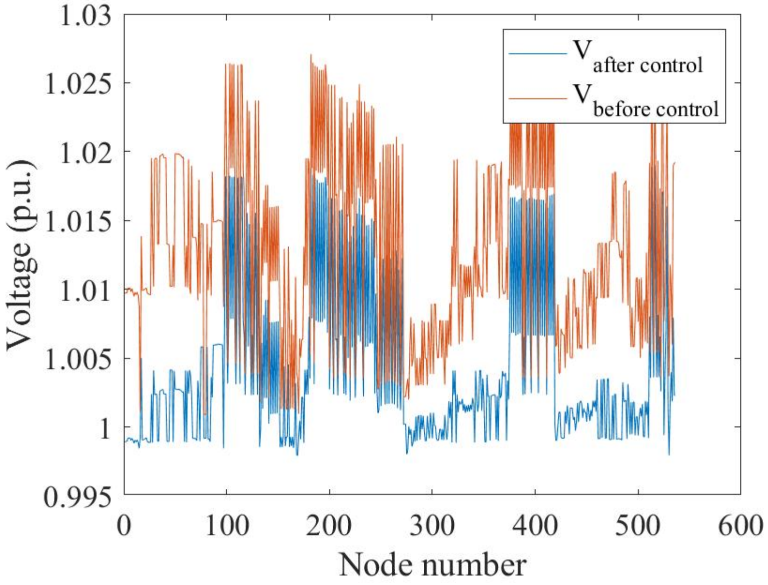
93.26% of the absolute errors smaller than 1%

Slow-Scale OMOO

Time series voltage control results



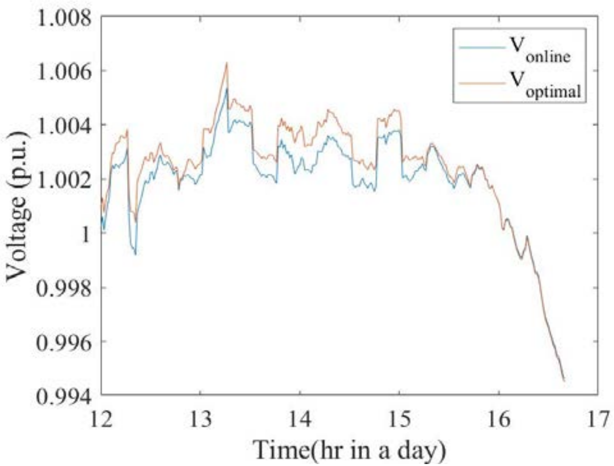
Snap-shot voltage control results



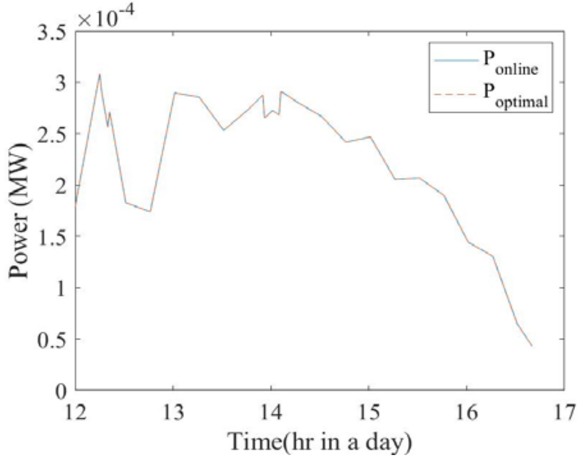
The voltage is closer to the voltage objective which is 1 p.u. after the slow-scale control is performed

Fast-Scale OMOO

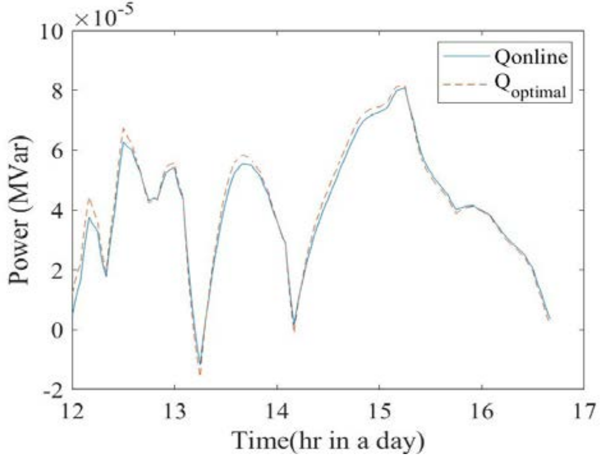
Time series voltage control results



PV P set point tracking profile



PV Q set point tracking profile

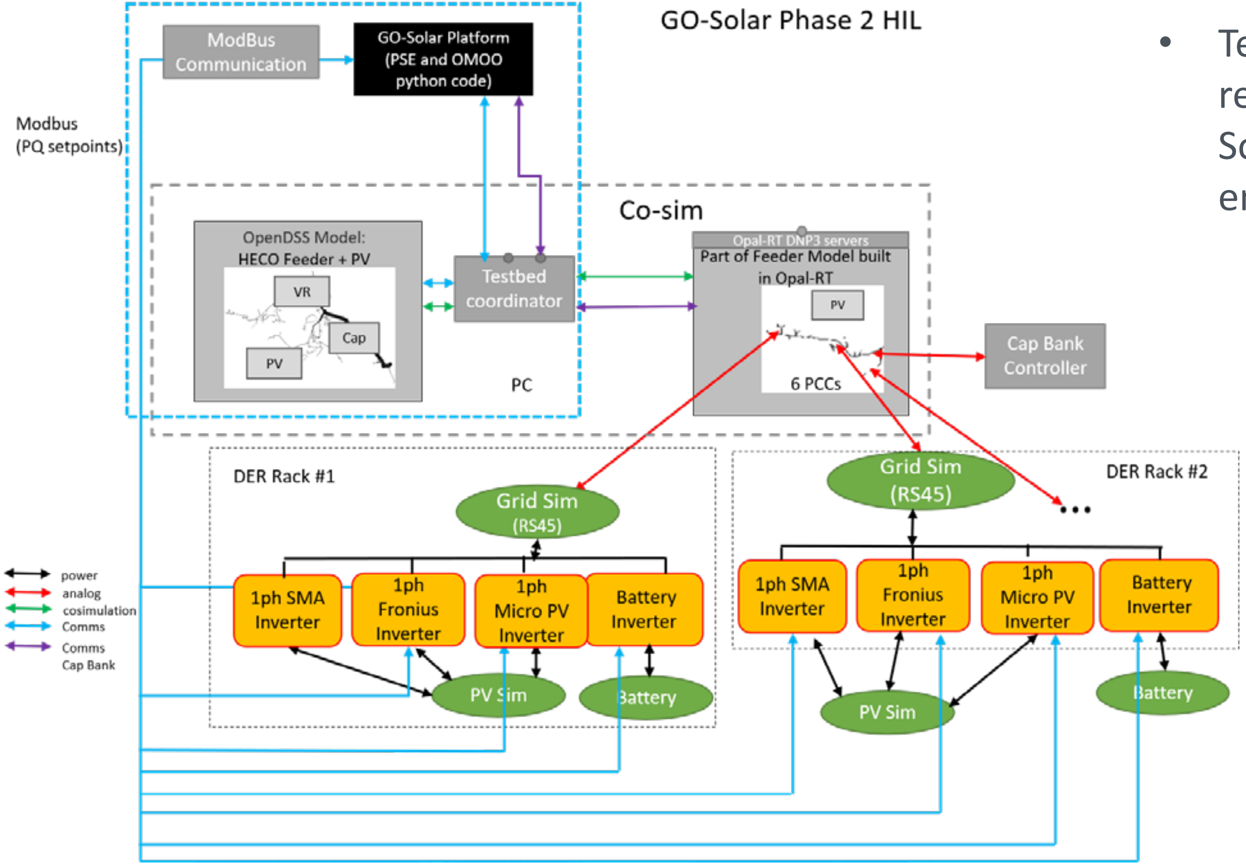


Tracking Error

	Voltage	PV P set point	PV Q set point
Tracking Error (%)	0.06	0.02	2

Hardware-in-the-Loop

ADMS Test Bed Setup for GO-Solar



- Test objective: evaluate voltage regulation performance of the GO-Solar Platform in a realistic testing environment
  - Accurate modeling of a full-scale distribution system of Mikulua 3 and sub-transmission system
  - Software control algorithm
  - 90 hardware PV and Battery inverters
  - Standard communication protocols

Schematic Diagram of the HELICS Architecture

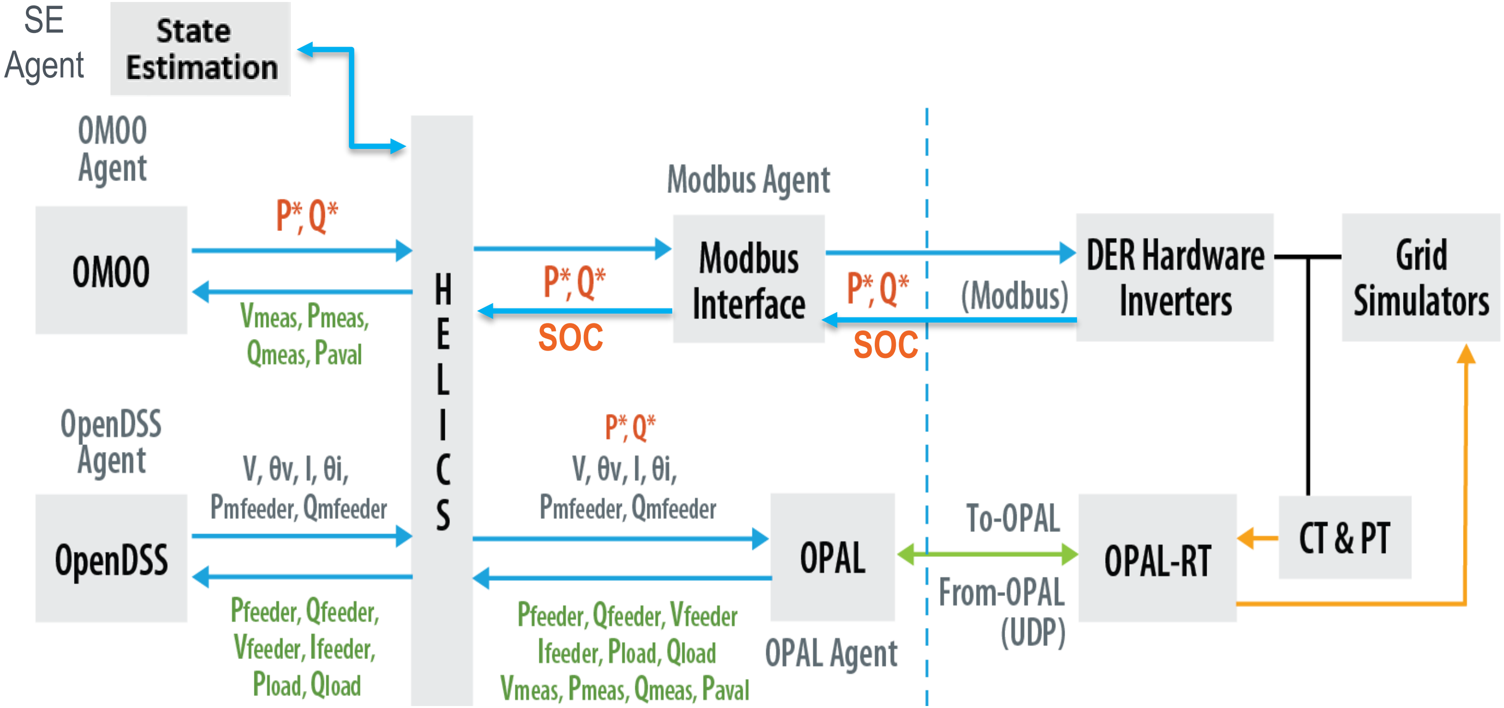
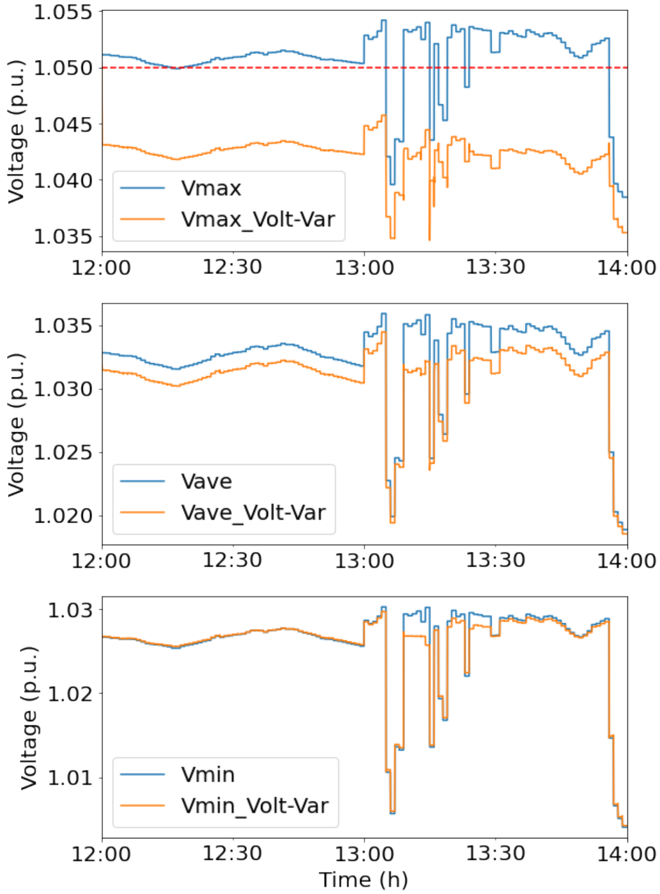
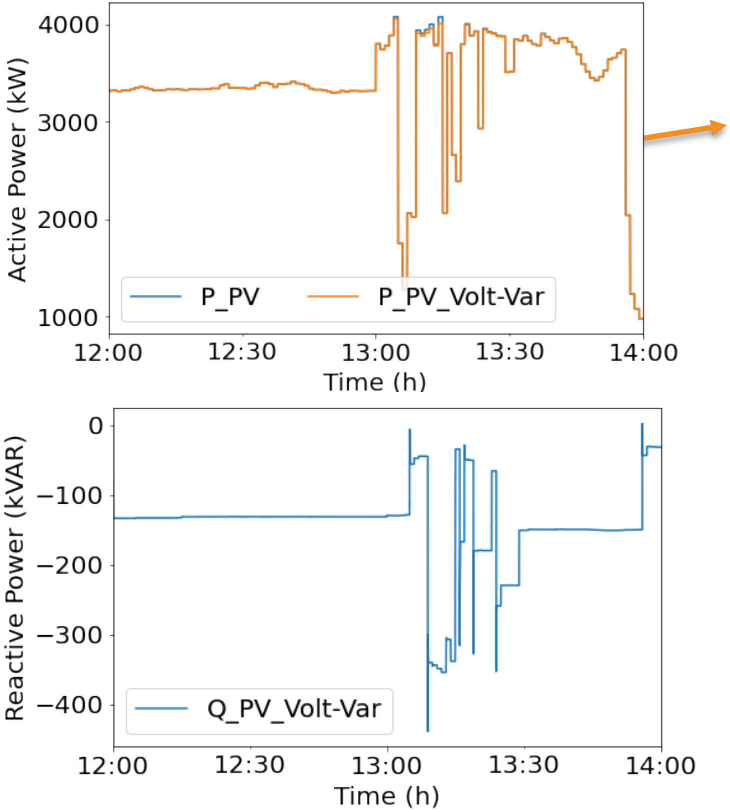


Photo of Hardware Setup for Six DER Racks/PCCs

HIL Testing Results – Scenario #1: Baseline Scenario





0.081% of total curtailment

Total PV measurements

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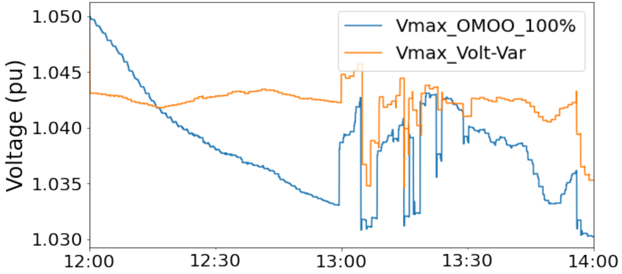
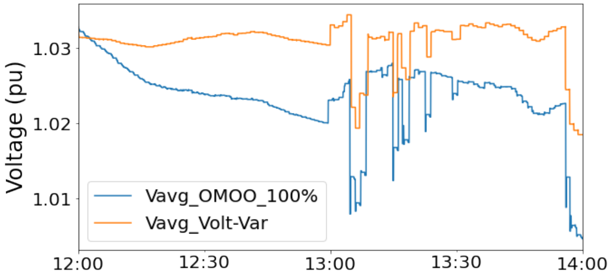
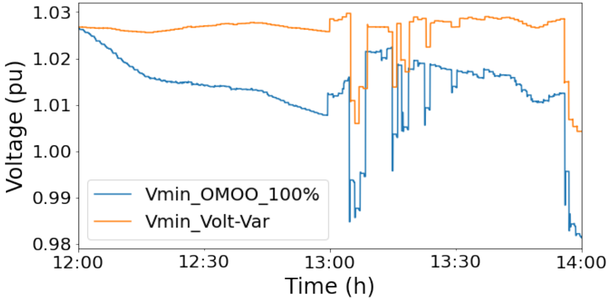
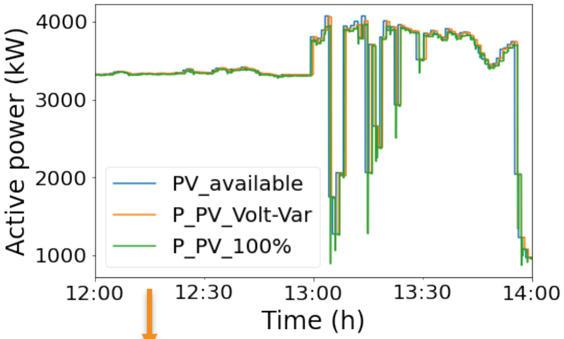
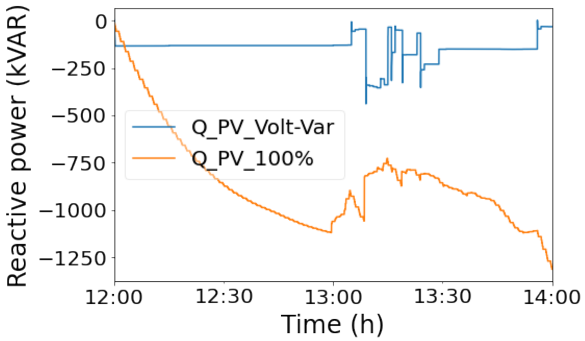
HIL Testing Results – Scenario #2: Control 100% PVs



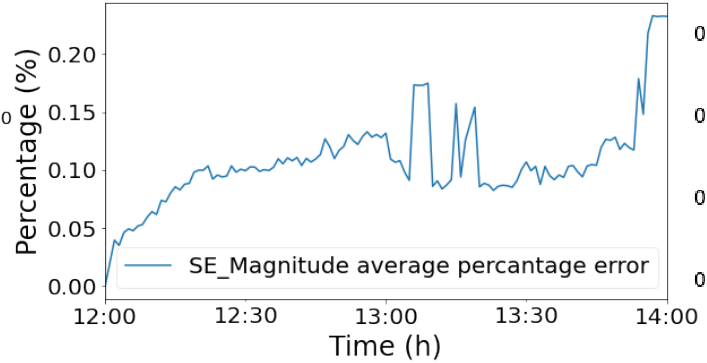


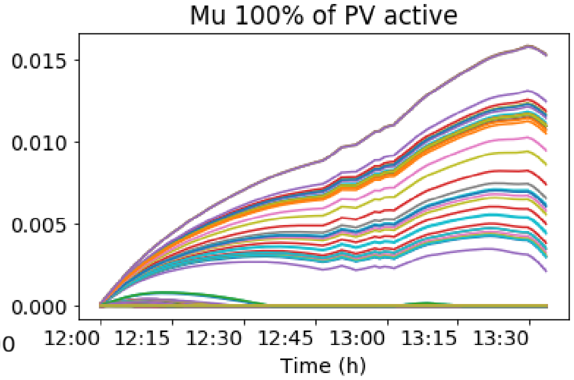




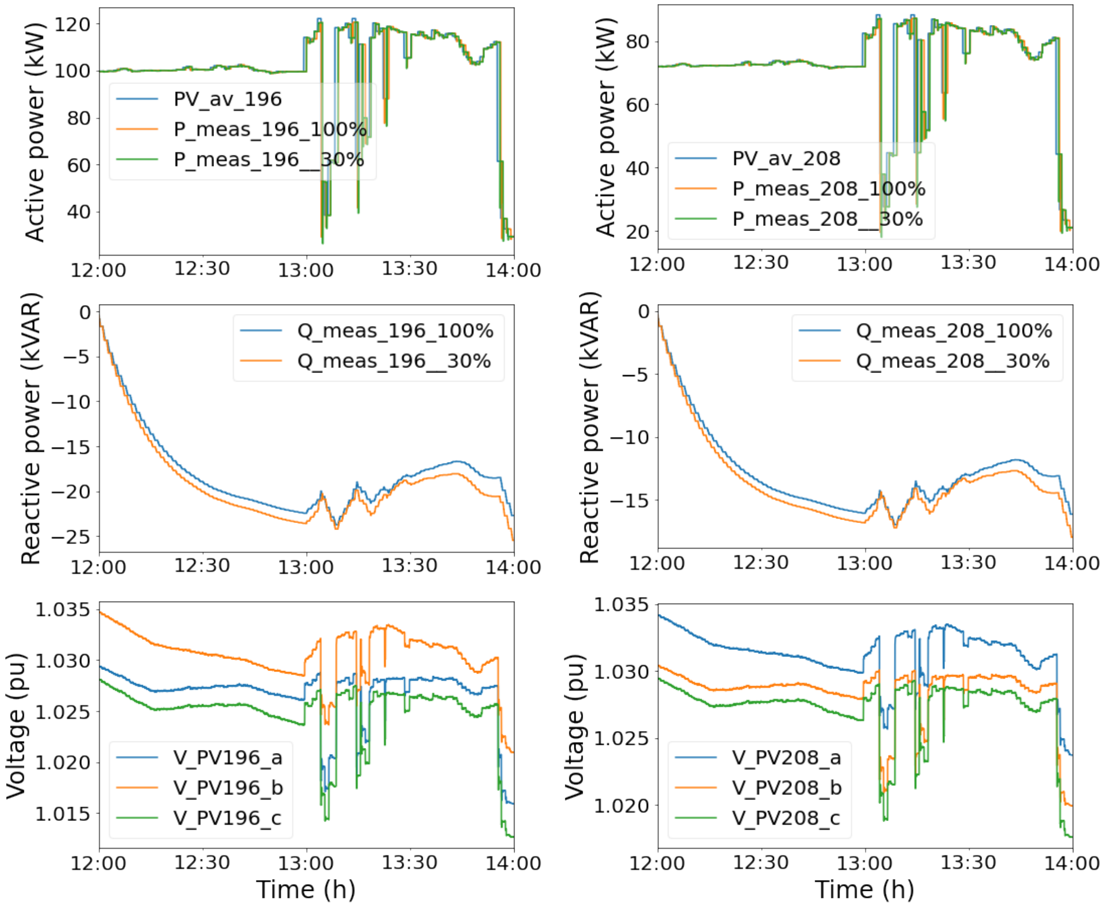


0.4% of total curtailment for OMOO and 0.081% for Volt-Var





HIL Testing Results – Scenario #3: Control 30% PVs

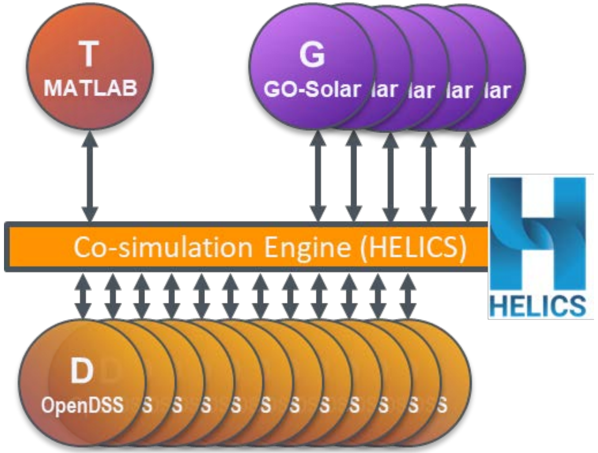


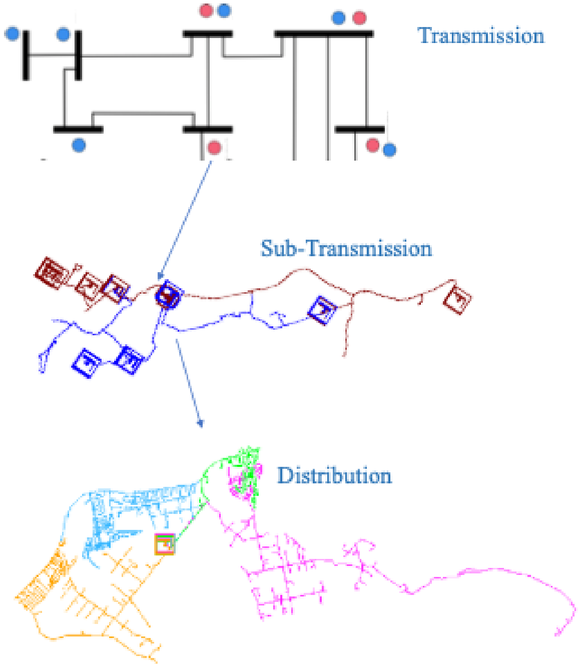
- The simulated PV inverters have similar responses in active and reactive power as the inverters in Rack #1, #2, #4, and #5.
- Confirm the simulated and hardware inverters work correctly.
- Higher reactive power outputs than the 100% PV scenario

Large-Scale Co-Simulation

Simulation Overview

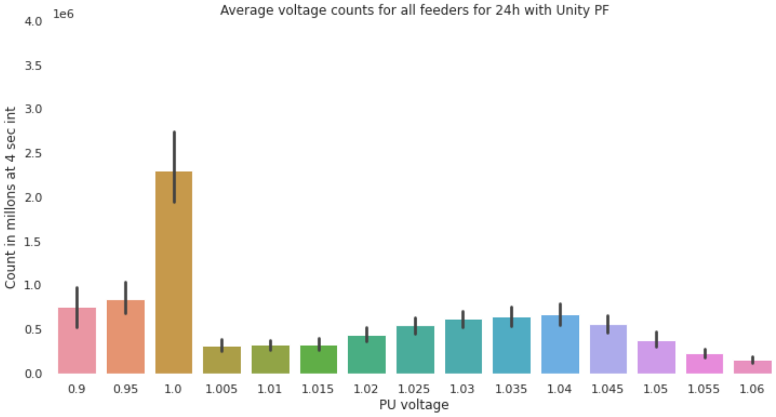
- 3 layered co-simulation using HELICS
  - Transmission (MATLAB)
  - Subtransmission (OpenDSS)
  - Distribution (OpenDSS)
  - For each OpenDSS network, a GO Solar Control Stack is assigned and included in the workflow



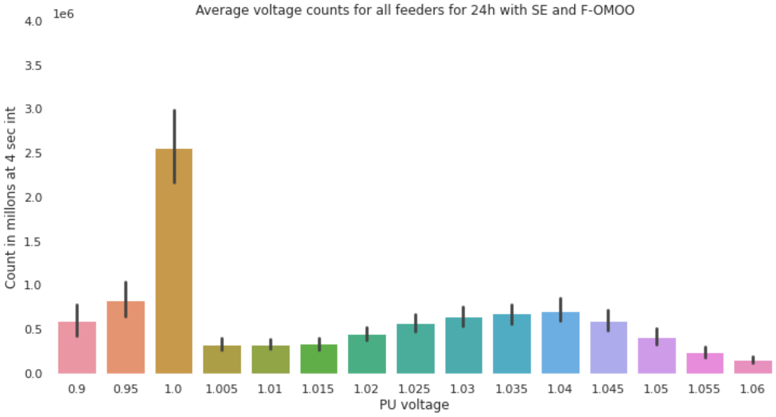


Representation Results – Voltage Controls

- Voltage distribution



Run time = 7 hours

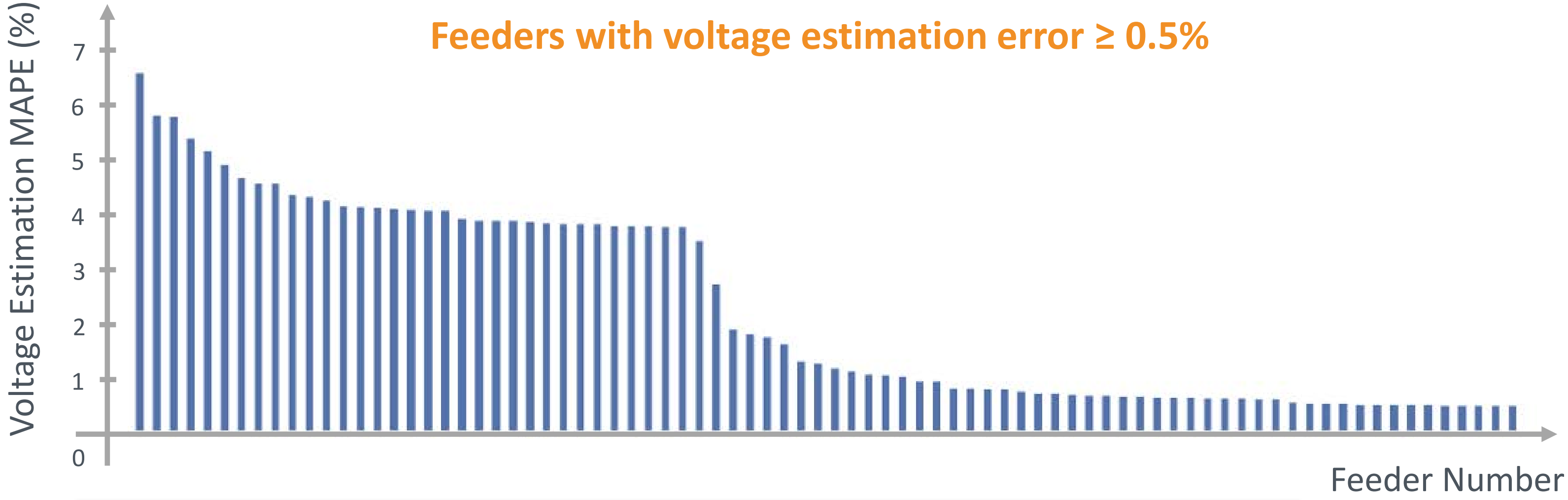


Run time = 12 hours

Voltages closer to 1 p.u. with less over/under voltage violations using GO-Solar

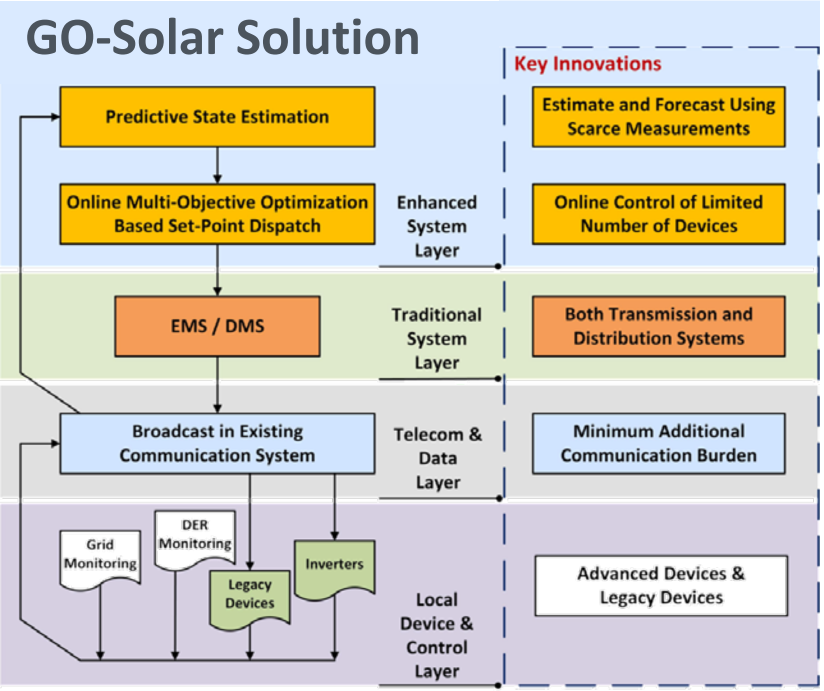
Representative Results – State Estimation

- State estimation accuracy
  - 80% of feeders with state estimation MAPE ≤ 0.5%
  - Larger voltage estimation errors due to larger voltage swings from the OMOO control points in some feeders



Accurate state estimation with limited measurements using GO-Solar

Summary



Key Accomplishments

- Real-time and predictive situational awareness from PSE
- Coordinated control of legacy devices and DERs
- Scalable solution for heterogenous measurements and controllers
- Large scale co-simulation and large scale HIL for extended performance testing

Achievement Highlights

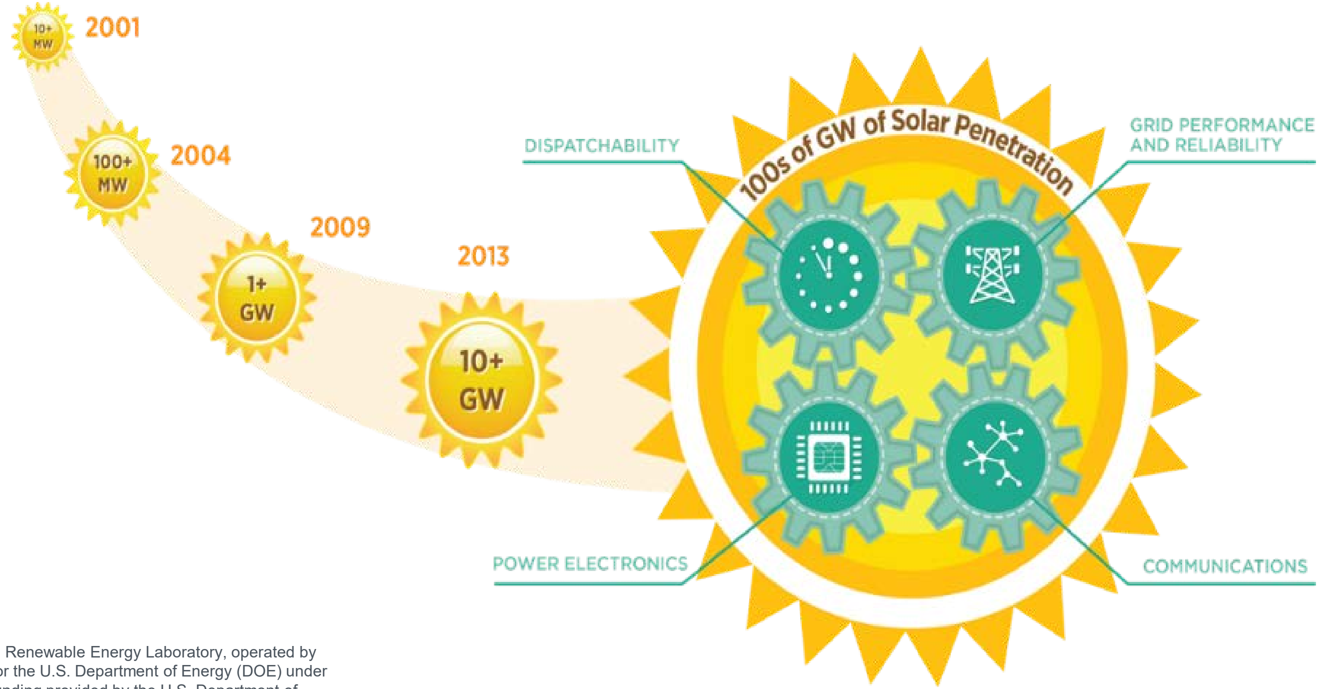
- **Publications**
  1. A. Bernstein, C. Wang, and J.-Y. Le Boudec, “Multiphase Optimal and Non-Singular Power Flow by Successive Linear Approximations,” Power Systems Computation Conference (PSCC), Dublin, Ireland, June 11-15, 2018. (Partly funded by the ENERGISE Go-Solar project and partly by the GMLC 1.4.10 [Control Theory] project.)
  2. A. Bernstein and E. Dall’Anese, “Bi-Level Dynamic Optimization with Feedback,” the 5th IEEE Global Conference on Signal and Information Processing (GlobalSIP), Montreal, Quebec, Canada, Nov. 2017.
  3. X. Zhu and Y. Zhang, “Coordinative Voltage Control Strategy with Multiple-Resource for Distribution Systems of High PV Penetration,” World Conference on Photovoltaic Energy Conversion (WCPEC-7), Waikoloa, Hawaii, June 10-15, 2018.
  4. Y. Zhang, A. Bernstein, and A. Schmitt, “State Estimation in Low-Observable Distribution Systems Using Matrix Completion,” HICSS-52 conference, Jan. 2019.
  5. B. Liu, H. Wu, Y. Zhang, R. Yang, and A. Bernstein, “Robust Matrix Completion State Estimation in Distribution Systems,” IEEE PES General Meeting, Atlanta, GA, Aug. 4-8, 2019.
  6. P. L. Donti, Y. Liu, A. J. Schmitt, A. Bernstein, R. Yang, and Y. Zhang, “Matrix Completion for Low-Observability Voltage Estimation,” IEEE Transactions on Smart Grid, IEEE Transactions on Smart Grid, vol. 11, no. 3, May 2020.
  7. M. Emmanuel and J. Giraldez, “Net Electricity Clustering at Different Temporal Resolutions Using a SAX-Based Method for Integrated Distribution System Planning,” IEEE Access, vol. 7, pp. 123689-123697, 2019.
  8. G. Cavraro, A. Bernstein, V. Kekatos and Y. Zhang, "Real-Time Identifiability of Power Distribution Network Topologies With Limited Monitoring," IEEE Control Systems Letters, vol. 4, no. 2, pp. 325-330, April 2020.
  9. X. Zhu, M. Emmanuel, G. Julieta, I. Krad, B. Palmintier, W.-H. Chen, A. Hirayama, and M. Asano “Realistic Distribution System Model Development for Integrated Transmission-Distribution Simulation,” the 47th IEEE Photovoltaic Specialists Conference (PVSC 47), June 14-19, 2020.
  10. Y. Liu, A. Sagan, A. Bernstein, R. Yang, X. Zhou, and Y. Zhang, “Matrix Completion Using Alternating Minimization for Distribution System State Estimation,” IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids, October 6-9, 2020.
  11. A. Sagan, Y. Liu, and A. Bernstein, “Decentralized low-rank state estimation for power distribution systems,” IEEE Transactions on Smart Grid, 2021.
  12. J. Wang, J. Simpson, R. Yang, B. Palmintier, S. Tiwari, and Y. Zhang, “Hardware-in-the-Loop Evaluation of an Advanced Distributed Energy Resource Management Algorithm,” the Twelfth Conference on Innovative Smart Grid Technologies, February 15-18, 2021.

- **Presentations**
  13. R. Yang, “Machine Learning-based Predictive State Estimation,” Virtual Workshop on Distribution and Transmission System Monitoring, U.S. Department of Energy, Solar Energy Technologies Office, Oct. 2020.
  14. R. Yang, “Predictive Analytics for Power Systems Decision Making,” IEEE Smart Grid Webinar, April 25, 2019. [Online].
  15. B. Palmintier, “Grid Optimization with Solar (GO-Solar) Experiences with: Data-driven and Machine Learning Approaches for High-pen PV Grids,” Workshop on Challenges for Distribution Planning, Operational and Real-time Planning Analytics for Small Scale PV Integration, U.S. Department of Energy, Solar Energy Technologies Office, Washington DC, May 15-16, 2019.
  16. R. Yang, “Data and Algorithms for Grid Optimization with Solar (GO-Solar),” Big Data Analytics Workshop, SLAC National Accelerator Laboratory, Dec. 10, 2018.
  17. Y. Zhang, “Predictive State Estimation – a Step Towards Proactive Operation of Power systems,” IEEE PES 2018.

- **Book Chapter**
  18. R. Yang and Y. Zhang, “Predictive Analytics for Coordinated Optimization,” to appear in Intelligent Power Grid of Tomorrow: Modeling, Planning, Control, and Operation, Springer.

- **Patent**
  19. R. Yang, Y. Liu, A. Bernstein, Y. Zhang, “Low-observability matrix completion” US Patent App. 16/246,998

Questions?



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