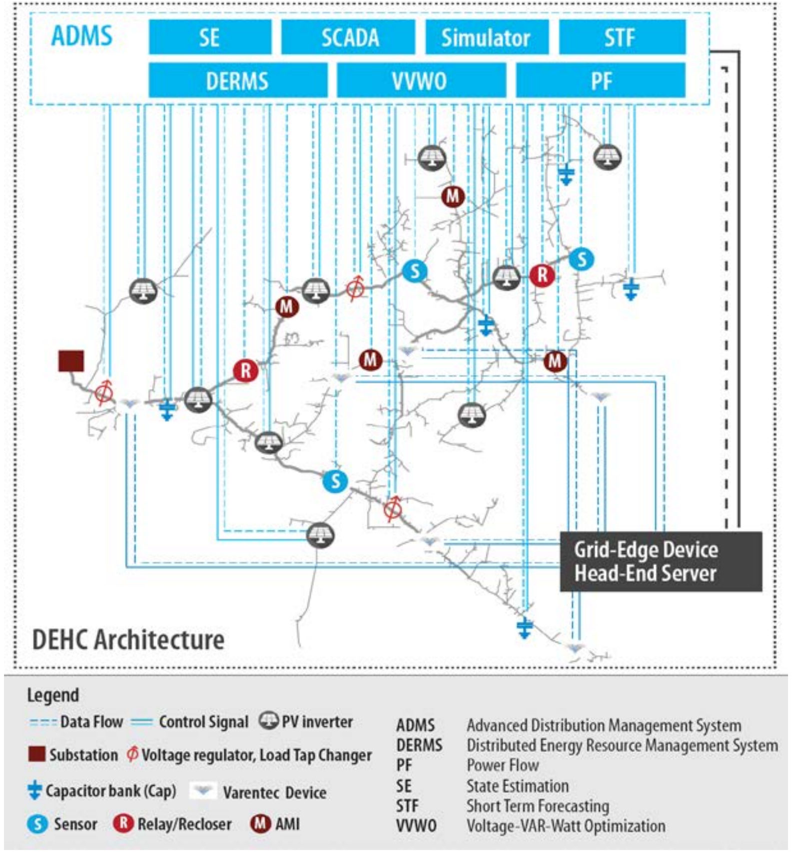
ECO-IDEA: Enhanced Control and Optimization of Integrated Distributed Energy Applications

Dr. Santosh Veda,
Group Manager, Grid Automation & Controls

ADMS Testbed Webinar Series

Outline

- Project Overview
- Simulations for Evaluating Data Enhanced Hierarchical Control (DEHC)
- HIL Demonstration of DEHC
- Taking DEHC to the field
- Techno-Economic Analysis



Project Team

- **DOE TMs:** John Seuss, Tassos Golnas
- **NREL** (Murali Baggu, Santosh Veda, Fei Ding, Harsha Padullaparthi, Jing Wang, Jiyu Wang, Ismael Mendoza, Soumya Tiwari, Francisco Flores-Espino, Valerie Rose)
- **Schneider Electric** (Scott Koehler, Svetozar Kobilarov, Milena Jajcanin, Filip Surla)
- **Varentec** (Rohit Moghe, Damien Tholomier, Hong Chun)
- **EPRI** (Jithendar Anandan, Brian Seal, Sean Crimmins)
- **Xcel Energy** (Brian Amundson, Andrew Wilson, Eric Gupta)

Enabling Extreme Real-Time Grid Integration of Solar Energy (ENERGISE)

PV Penetration

>15% peak load, >125% min load, >20% energy production

Reliability

SAIDI/SAIFI, ANSI 84.1

Scalability

>= 10k active nodes, >= 100 physical controllable nodes

Observability

System State observed every 10 minutes; hourly forecasts

Interoperability

Enterprise-level CIM

Device-level DNP3

Computation Cycle

Real-time operation <1min

Response Time

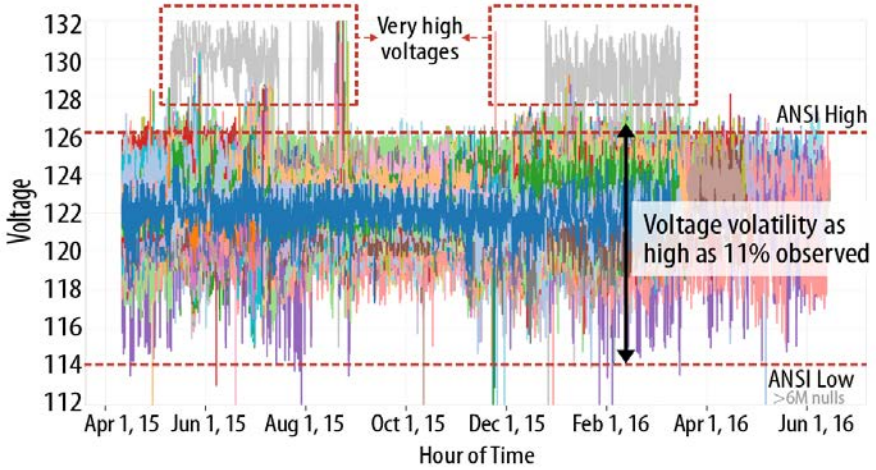
Local <10sec, Network <30 sec, System level <1 min, Enterprise level <5min

What is the Problem?

- ❑ Overvoltage conditions
- ❑ Transients from variability of renewable generation
- ❑ Stochasticity of loads

Weaknesses:

- ❑ lack of situational awareness
- ❑ heuristic and slow-acting control
- ❑ latency of control for emergency
- ❑ Do not tap into communications



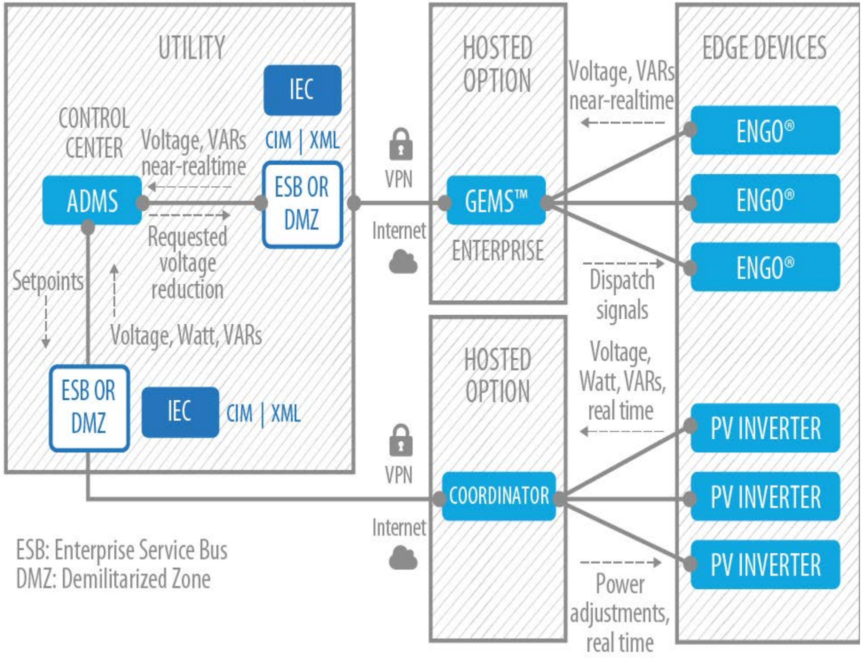
Voltage variability at the grid edge measured by 1,005 AMI meters collected over 14 months

Project Overview

- The project targets to develop and validate a novel ***Data-Enhanced Hierarchical Control (DEHC)*** architecture for distribution grids with high PV penetration.
- The DEHC architecture represents a hybrid approach of ADMS-based centralized controls, grid-edge controls and distributed controls for PV inverters.

DEHC features:

- ADMS-centered operations,
- Synergistic ADMS-grid edge operations,
- PV fast-regulation capabilities,
- Comprehensive situational awareness,
- Cybersecured and interoperable.



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NREL
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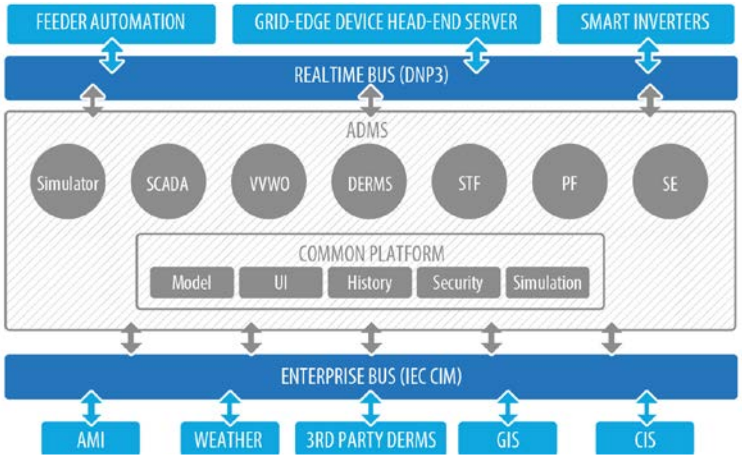
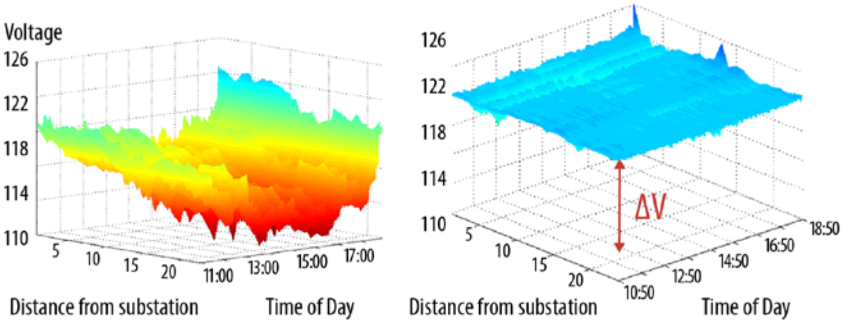
ADMS – ENGO Synergy

- Advanced applications for network analysis, diagnosis, prognosis, and control
- Advanced model-based optimizations
- Commands to field devices such as tap changers, capacitors, smart PV inverters
- Varentec's ENGO® devices: increased flexibility in controlling voltage profile
- Interface between GEMS™ and ADMS to achieve coordination
- Standard protocols such as DNP3 to achieve interoperability

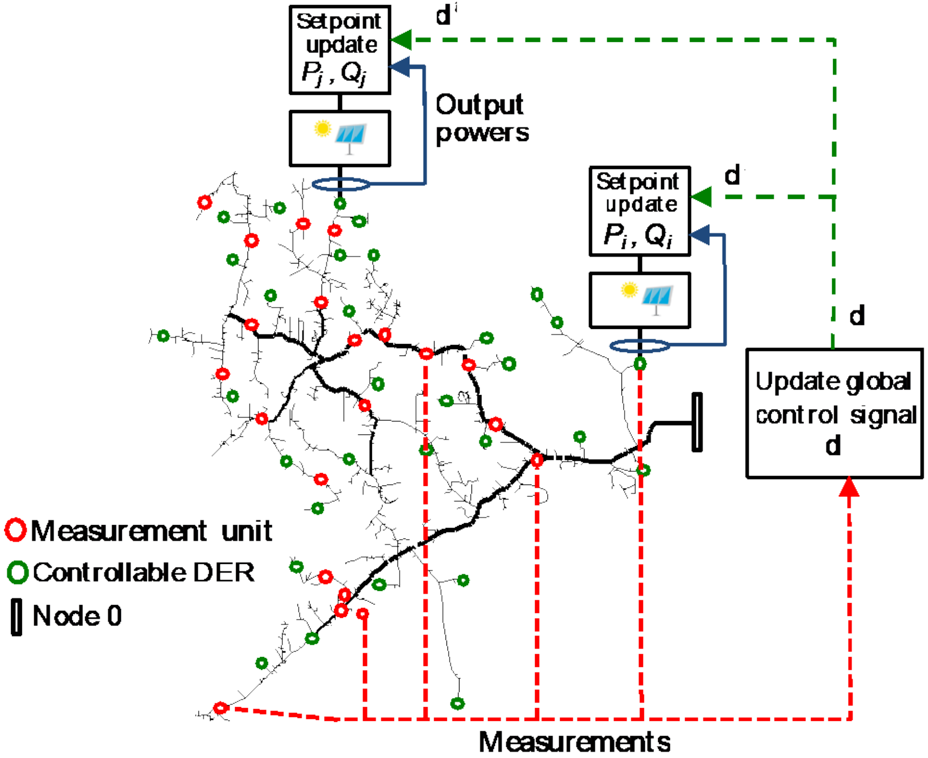




Real-time optimal power flow (RT-OPF)

arpa·e

Network Optimized Distributed Energy Systems (NODES)

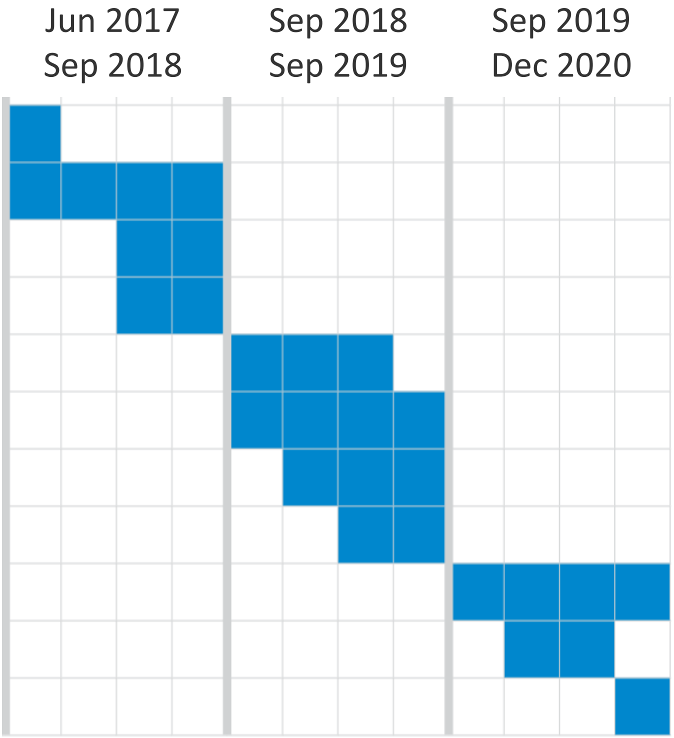


- **Unique contribution of our team**
  [Dall'Anese at al'14, Bernstein at al'14]

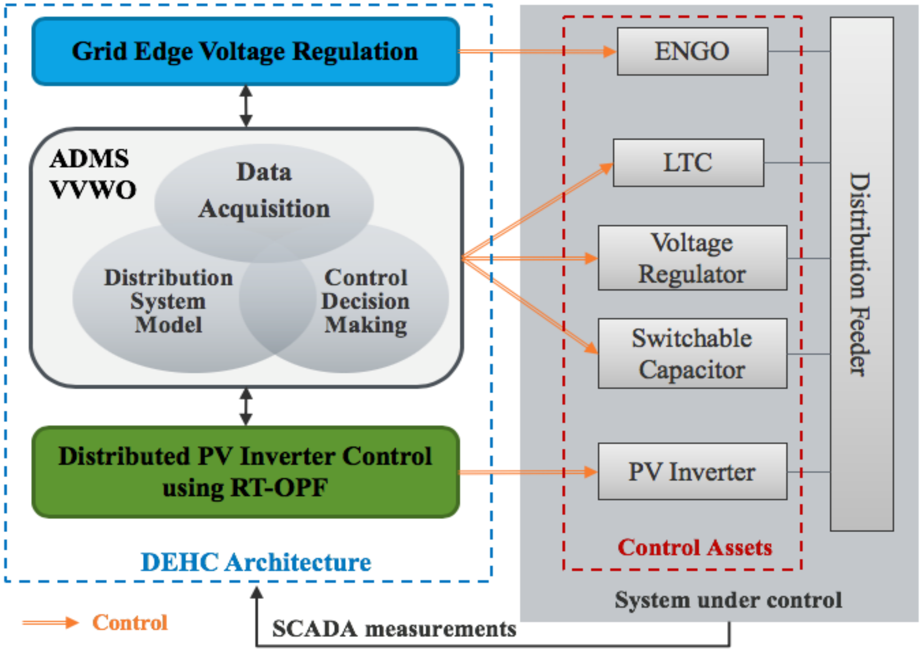
- Real-time (second level)
- Modular
- Distributed
- Stable
- Optimal

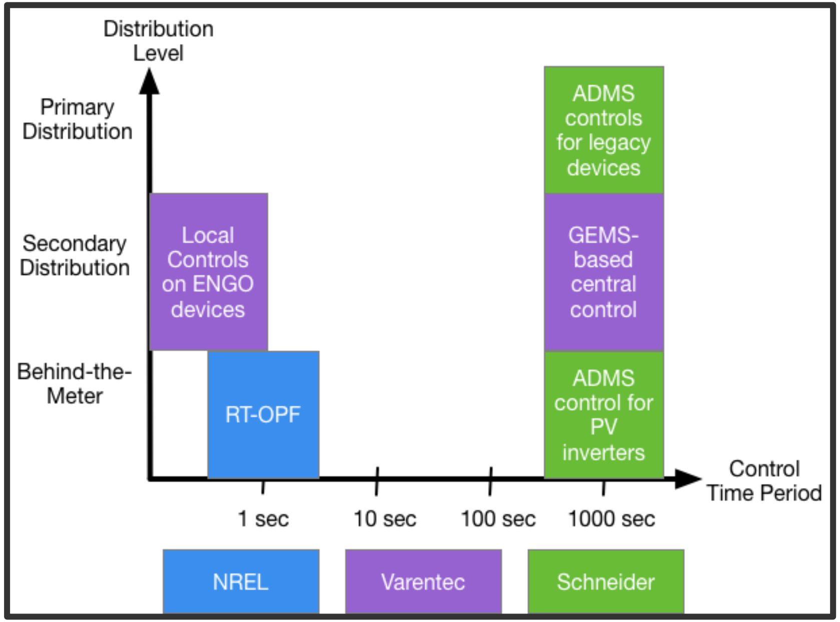
Project Phases

- ✓ Budget Period 1 – Architecture Development (completed)
  - Develop and validate the Data-Enhanced Hierarchical Controls (DEHC) architecture using software simulations
  - Develop test plans for evaluating the functionality, interoperability & cybersecurity
- ✓ Budget Period 2 – Simulations & HIL (completed)
  - Implement DEHC architecture, interoperability and cybersecurity through HIL at NREL's ESIF
  - Finalize field deployment on Xcel Energy's feeders
- ✓ Budget Period 3 – Field Deployment and Analysis (current)
  - Perform field deployment and validation
  - Analyze results and perform techno-economic analysis
  - Demonstrate DEHC through HIL

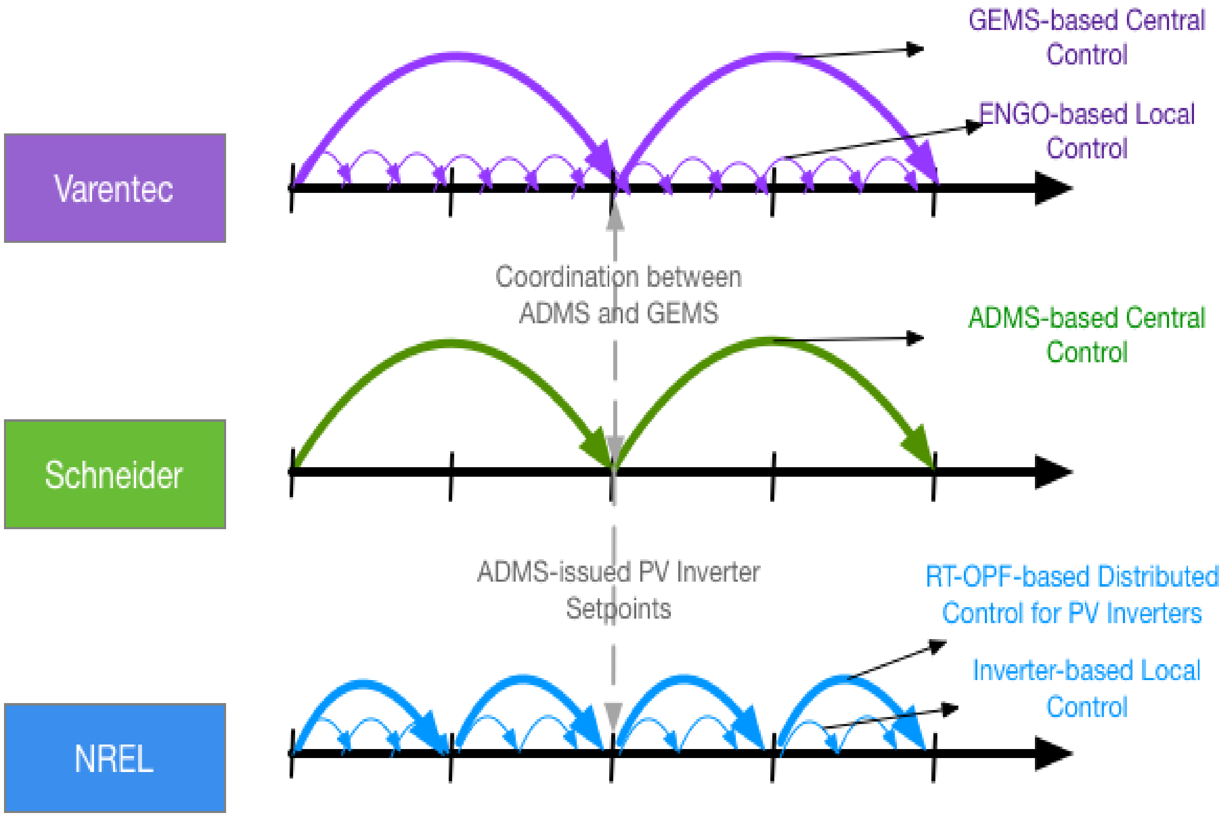


DEHC Architecture Overview

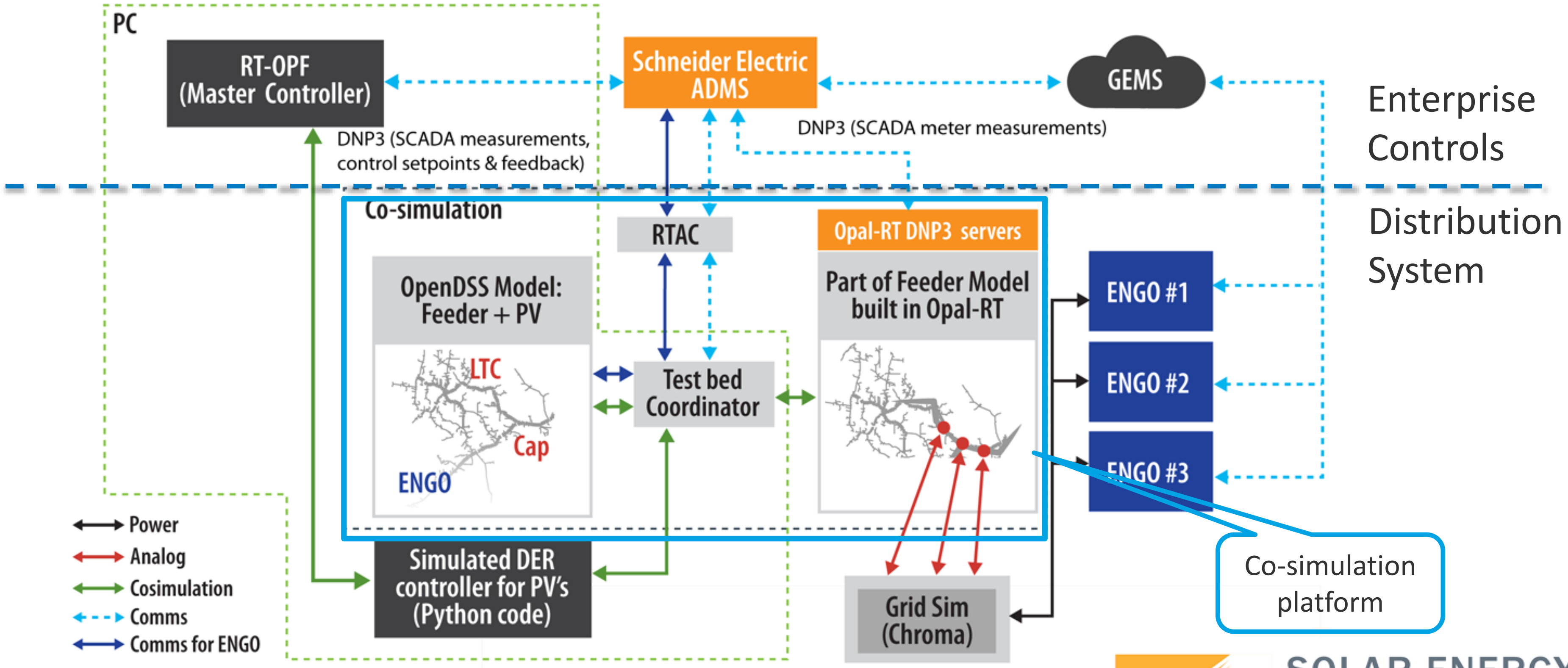




DEHC Controls Exchange



HIL Implementation Using ADMS Test Bed



ADMS Test Bed Implementation for ECO-IDEA

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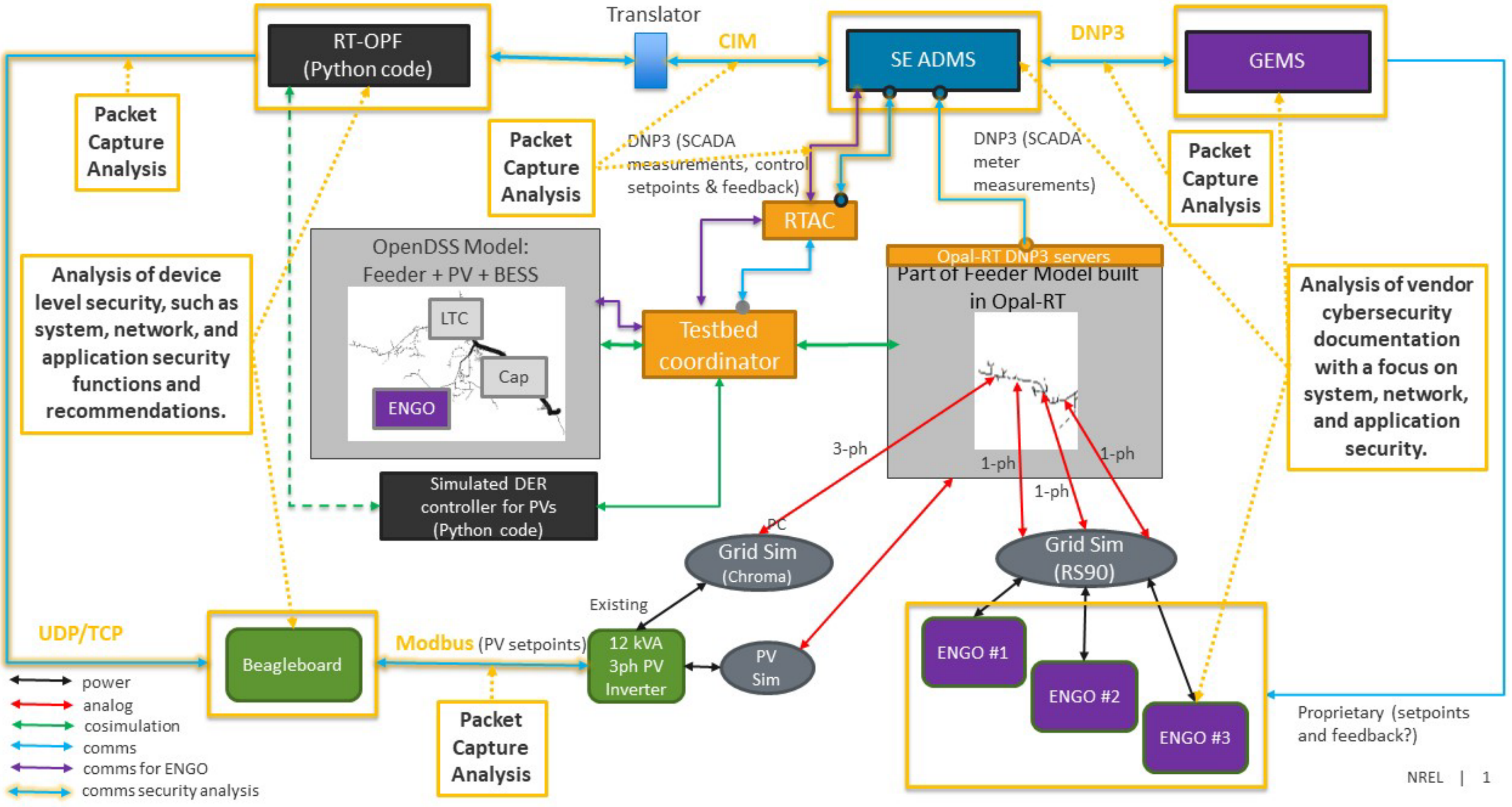
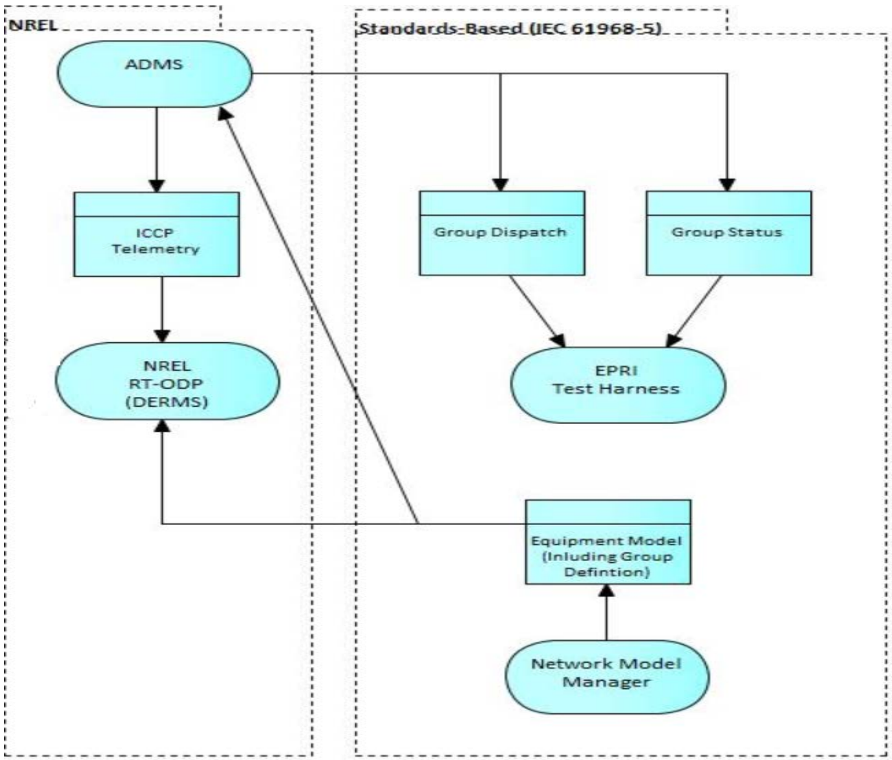
Cybersecurity Analysis



Interoperability Testing



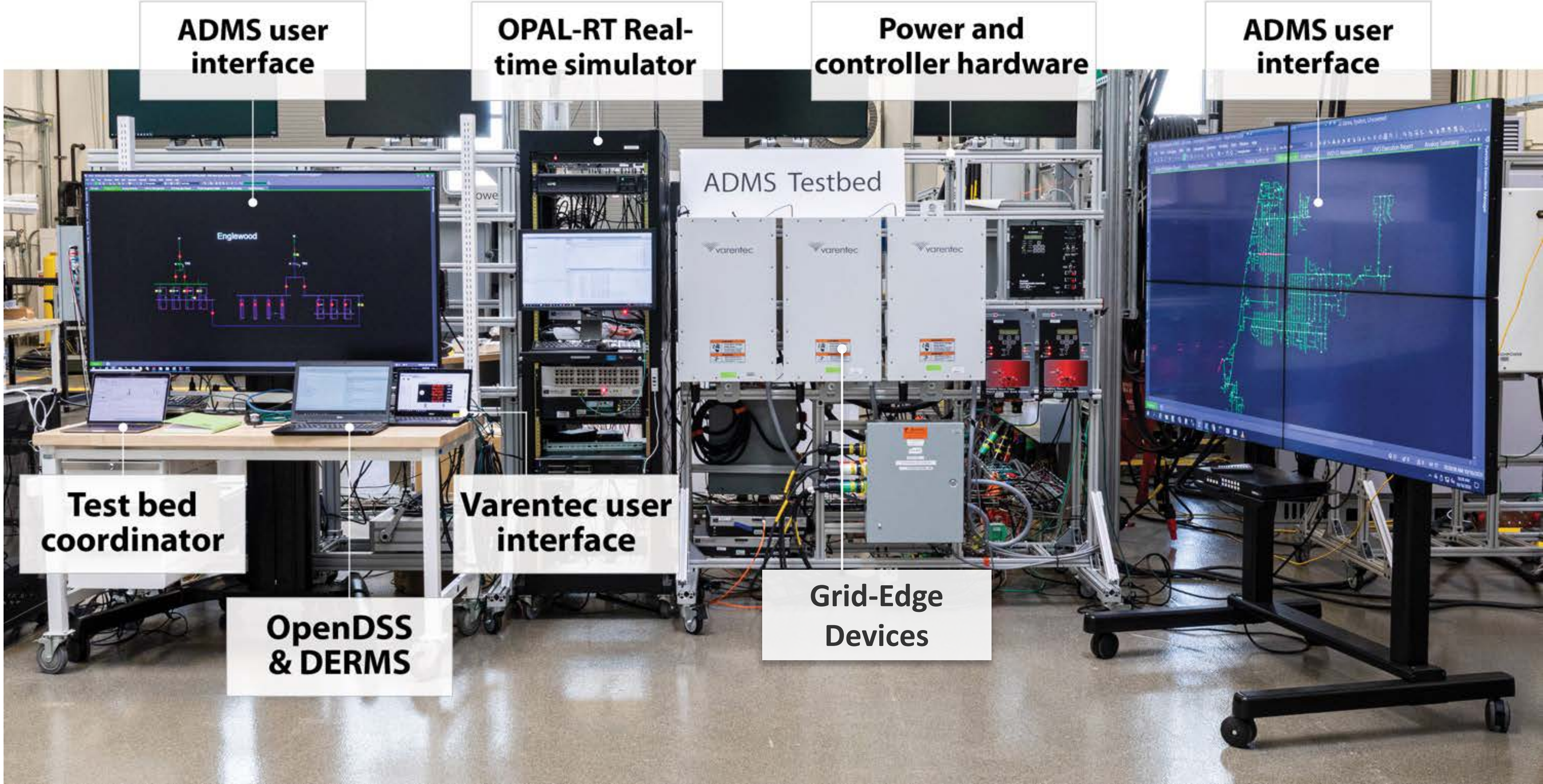
- **ADMS to RT-OPF Interface**

- **RT-OPF Data Telemetry (ICCP)**
- Voltage magnitude at selected measurement locations
- **RT-OPF Group Dispatch (61968-5)**
- ADMS Group Dispatch to PV Inverters
- **RT-OPF Group Status (61968-5)**

  Measurement values for ADMS
- **RT-OPF Network Data Model (61968-5)**

  Network equipment data

Lab Infrastructure



Simulations for Evaluating DEHC

Simulation Scenarios

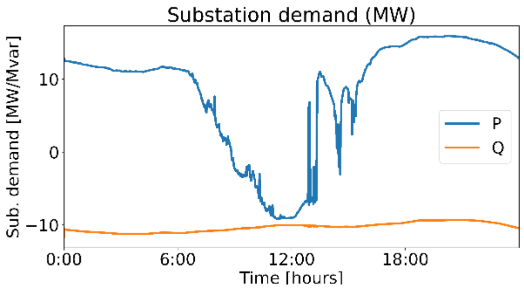
- Baseline: Legacy assets operate in local control mode, no ENGOs
- S1: ADMS controls both legacy assets and ENGO unit setpoints, PV smart inverters in local volt/var mode
- S2: RTOPF issues setpoints to PV smart inverters

Scenario	Legacy devices	ENGO units	PV smart inverters
Baseline	Local control	×	Unity power factor
S1	ADMS	ADMS	Local volt/var control mode
S2	ADMS	ADMS	RTOPF

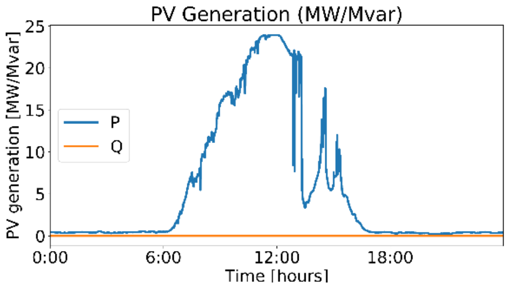
Baseline Results

- High voltage exceedances observed at more than 400 customer locations
- No low voltage exceedances observed
- LTC was in local control mode (without line drop compensation enabled)

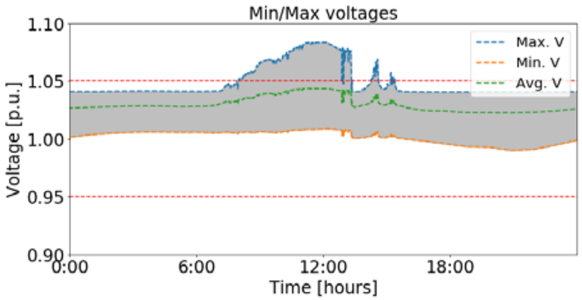
Demand at substation



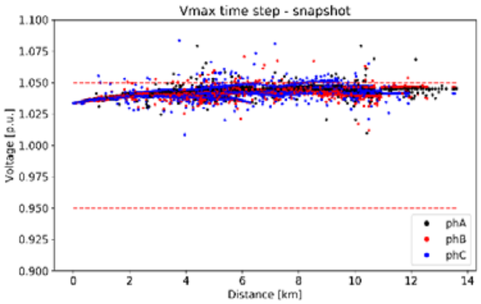
PV generation



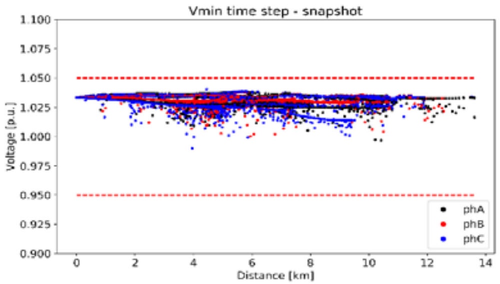
Voltage distribution

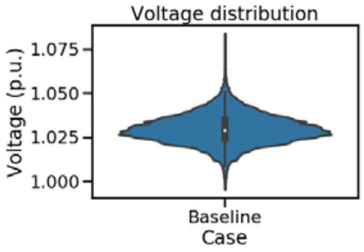


Voltage profile at Vmax time



Voltage profile at Vmin time

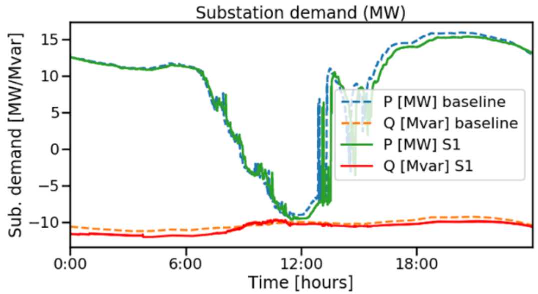




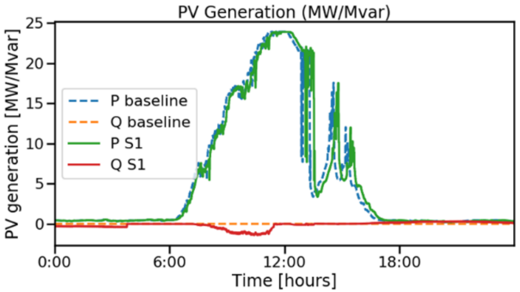
ADMS/UPF (S1) Results

- Voltage profile is improved considerably due to ADMS lowering the LTC tap position
- High voltage exceedances observed at 26 customer locations
- Since PV inverters are operated in local volt/var control mode, the PV active power curtailment is 0%

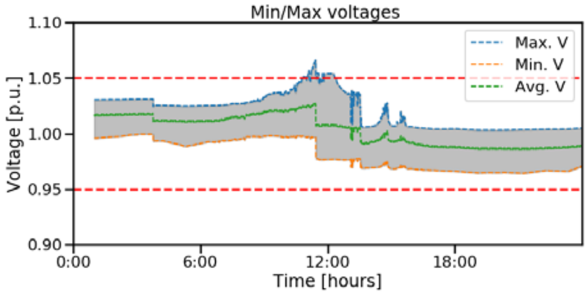
Demand at substation



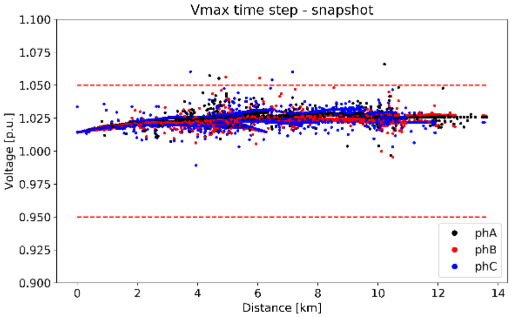
PV generation



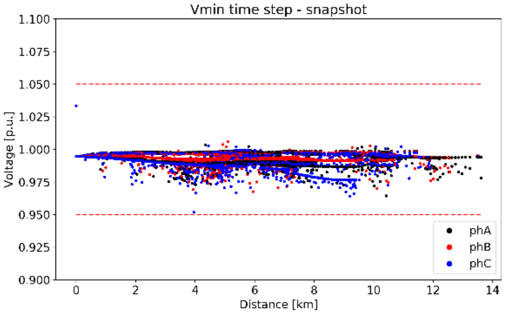
Voltage distribution

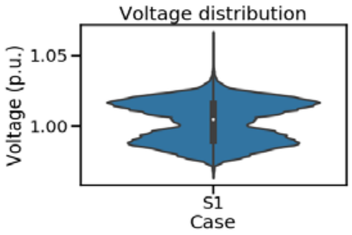


Voltage profile at Vmax time step



Voltage profile at Vmin time step

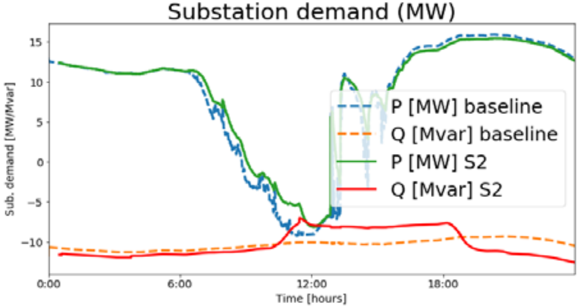




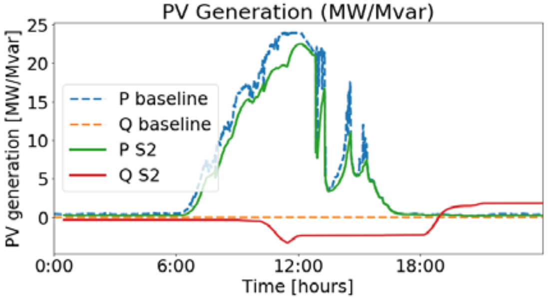
ADMS/DERMS (S2) Results

- A peak active power curtailment of 4.8 MW (~20% relative to baseline peak generation of 23.9 MW) is observed compared to baseline for voltage regulation
- All the bus voltages are within limits. Legacy device setpoints are same as in S1.

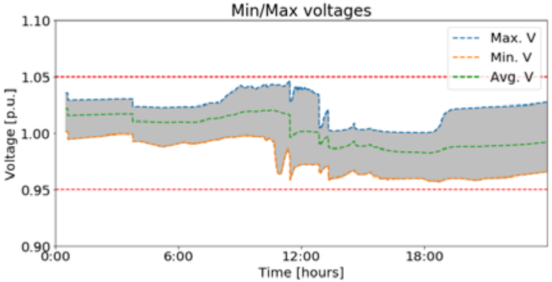
Demand at substation



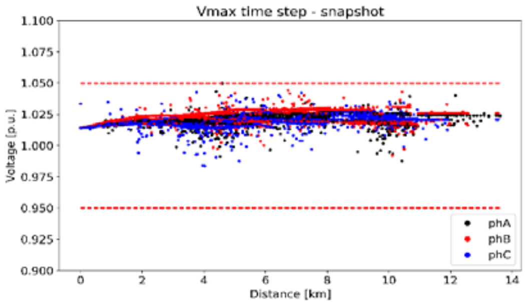
PV generation



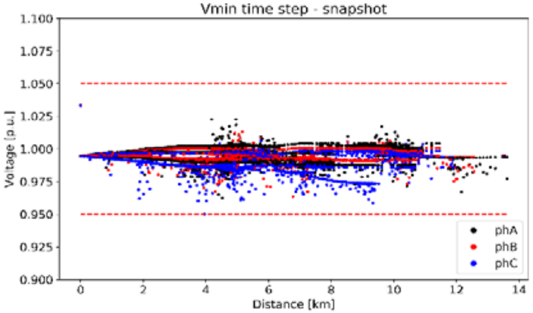
Voltage distribution

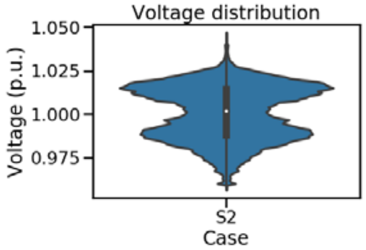


Voltage profile at Vmax time



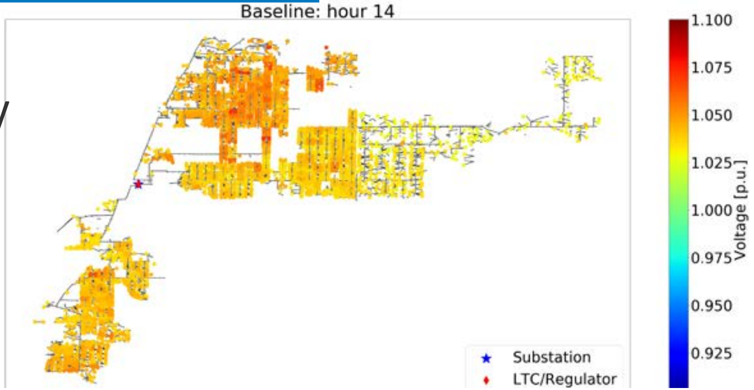
Voltage profile at Vmin time step

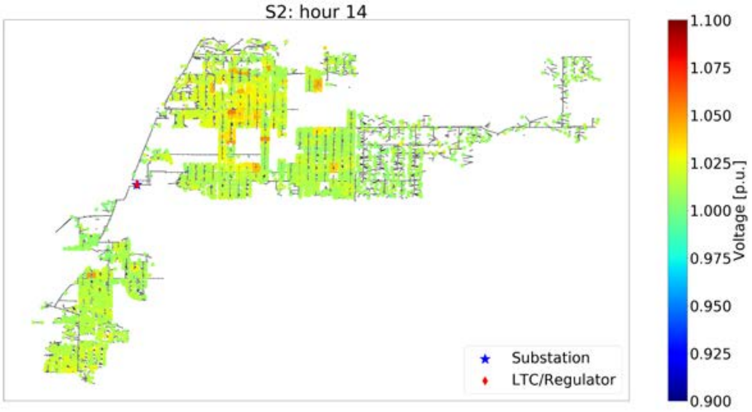


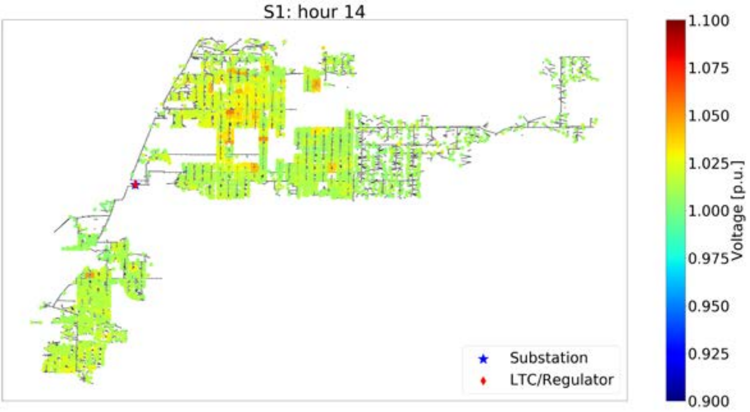


Worst-case Operation

- Clockwise (starting on the right):
  - Baseline (high PV; no ADMS/GEMS/PV control
  - S1 (ADMS + GEMS + Volt-VAr-Watt control for PV)
  - S2 (ADMS + GEMS + DERMS)







Simulations Outcomes

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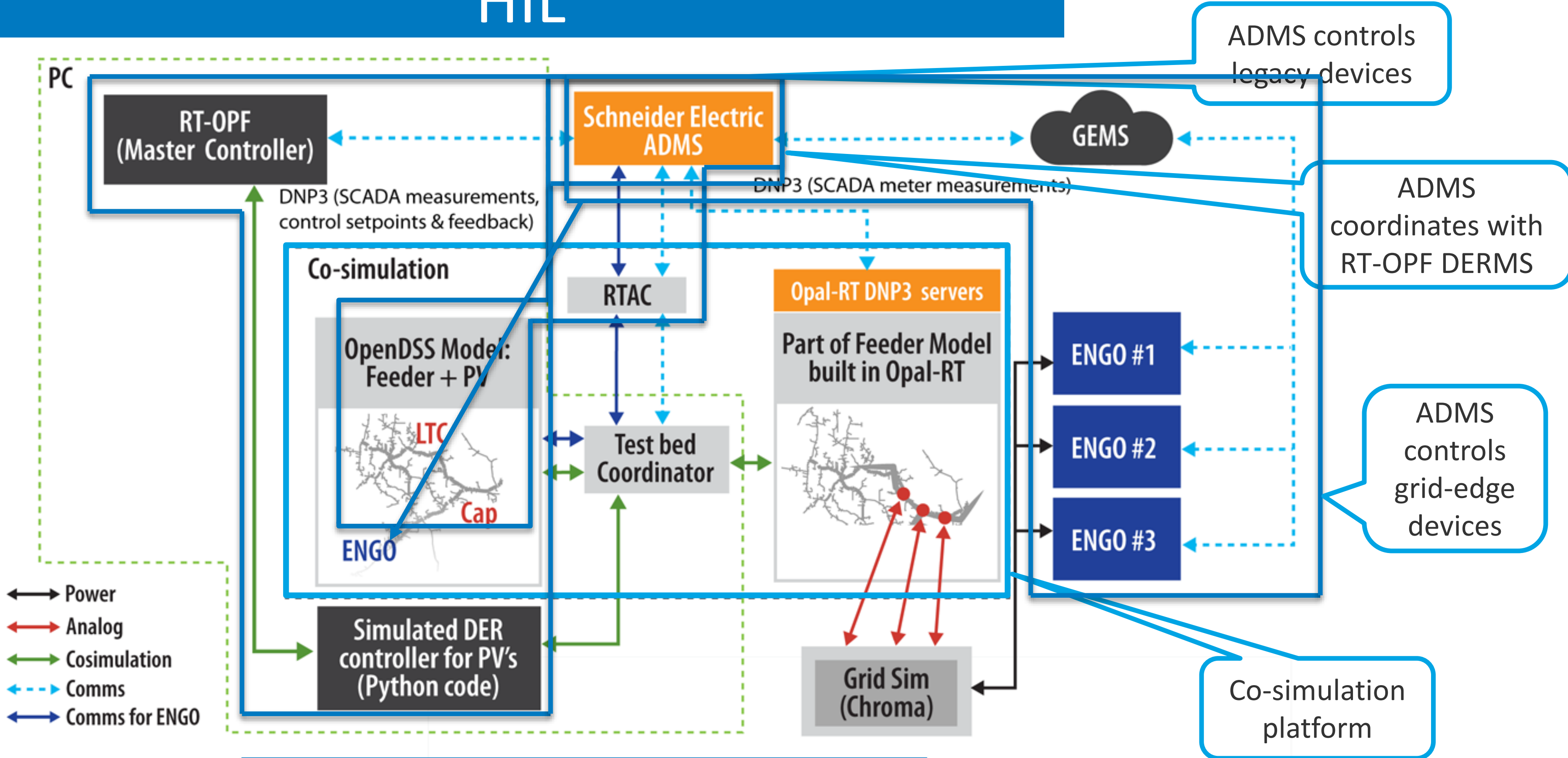
- The simulations demonstrate the effectiveness of DEHC architecture for voltage regulation
- The local volt/var control of PV smart inverters alone cannot resolve the voltage issues, even with ADMS control of legacy devices
- ADMS control of legacy devices coupled with fast regulation of PV smart inverters using RTOPF showed improved voltage regulation
- Coordination with PV inverters is important for system-level services like CVR, voltage regulation

HIL Demonstration of DEHC

Demonstrating PV Control through HIL

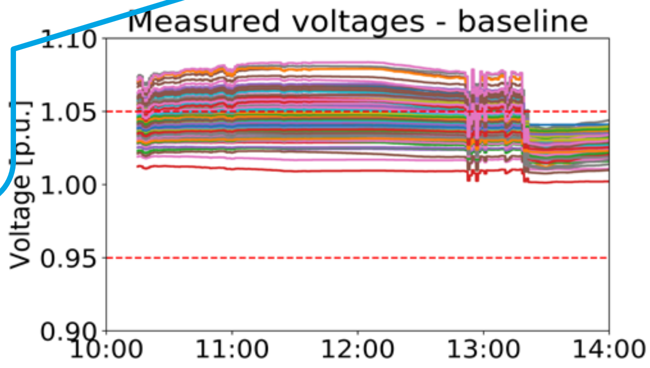


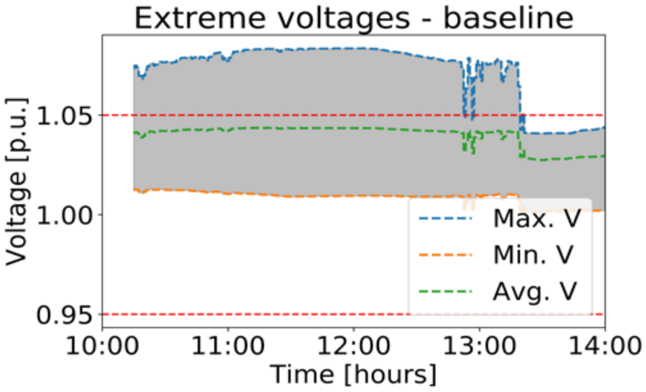
ADMS Test Bed Implementation for ECO-IDEA

HIL Test Results

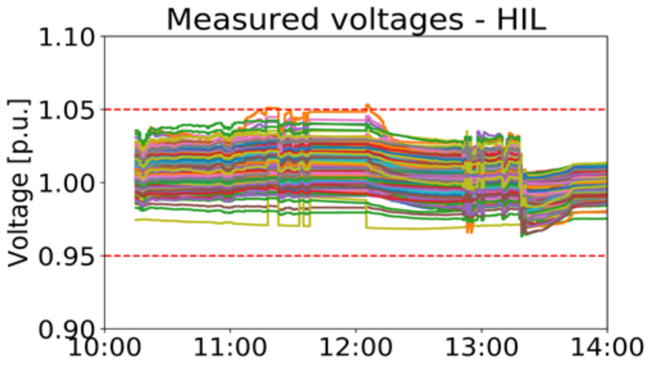
No ADMS control: LTC and Cap Bank local control, no ENOGs, PV local control

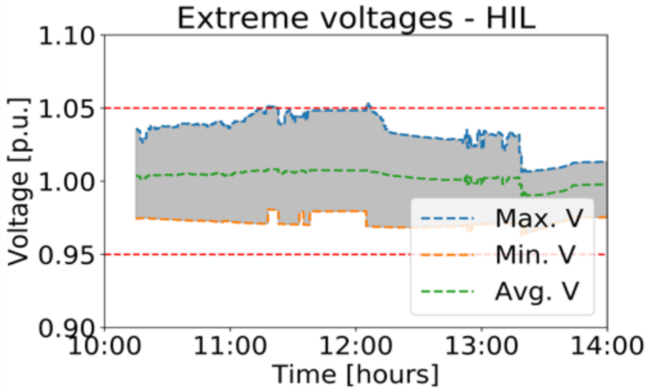
Baseline





ADMS-centered operation HIL test





HIL Test Results

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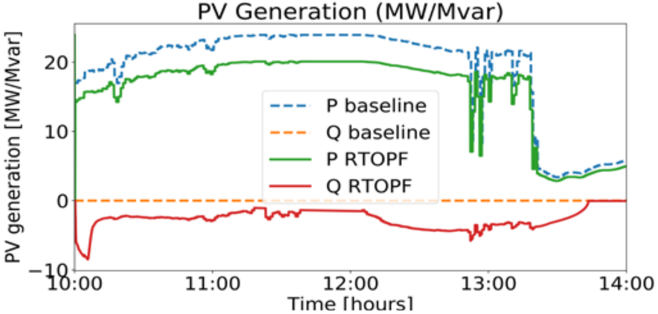
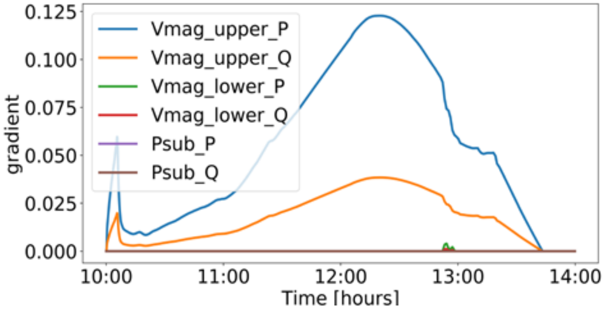
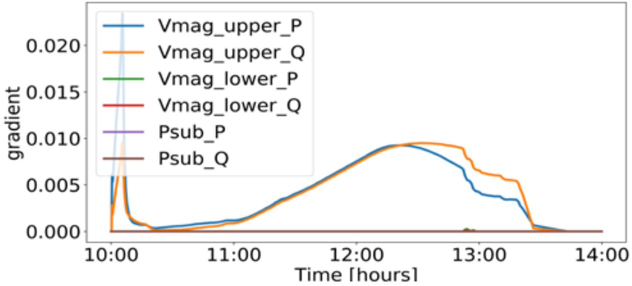
Total PV generation



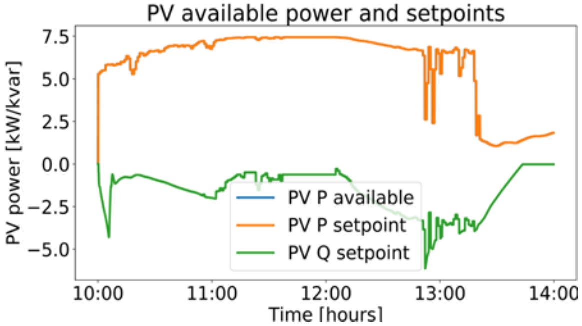
RTOPF coordinator outputs

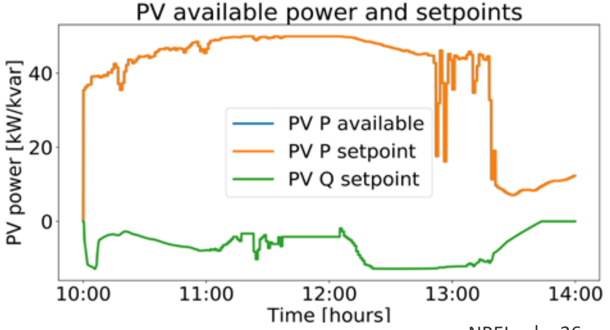




- The RTOPF algorithms (coordinator and local controllers) converge and work as expected to regulate system voltages

RTOPF PV local controller outputs





Taking DEHC to the field

Field Demonstration in Denver Metro

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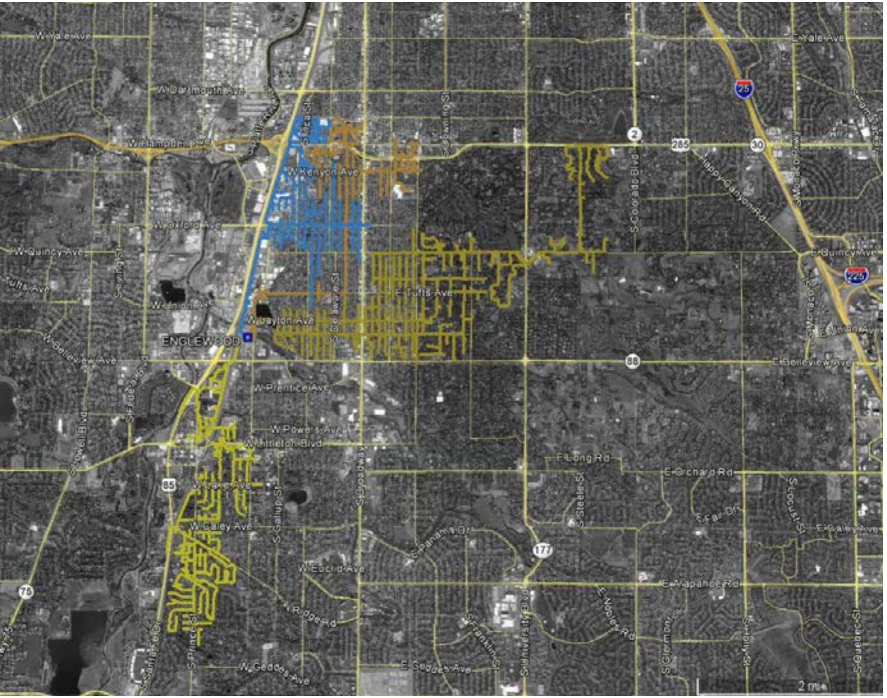

Photo credit: Xcel Energy

Englewood Bank 2 field deployment status and schedule:

- ADMS is currently autonomously running 24/7 VVO
- All devices installed in preparation for IVVO.
- AMI bellwether meters were installed. Limited scope installation on residential customers.
- Integration between AMI and ADMS will be completed in late Q1 2020.
- Upgraded LTC control installed at substation transformer. SEL 2411 allows the ADMS to issue a set point which the LTC will regulate the secondary voltage to.
- 18 primary capacitor banks installed.
- 144 ENGOs have been installed

Field Evaluation Plan

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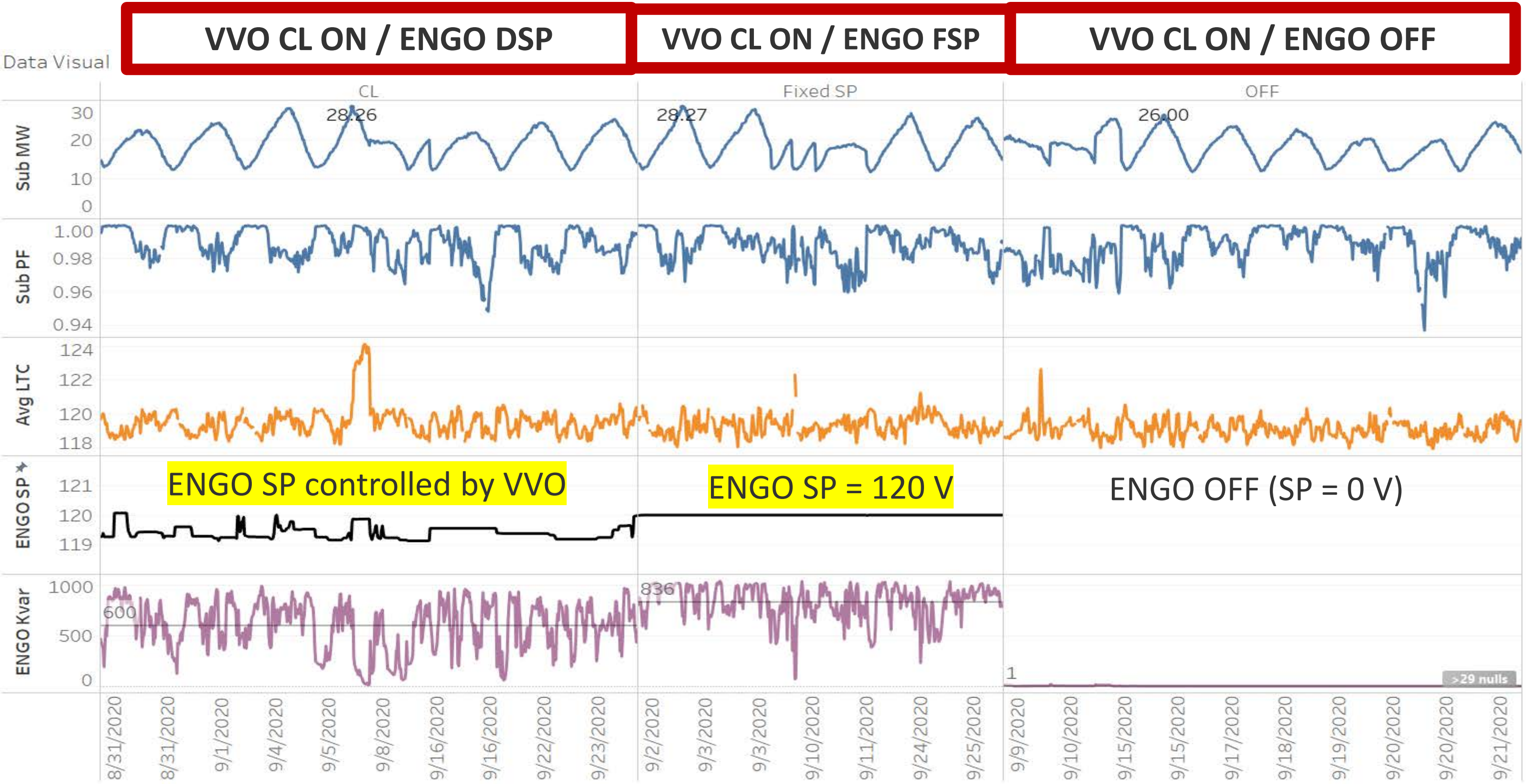
- Automatic testing process consists of multiple testing cycles
- Each testing cycle considers 5 days of testing - each day of testing consists of monitoring the network state with a different combination of centralized and decentralized control

One testing cycle	VVO CL status	ENGOs status	ENGOs setpoint
Day 1	OFF	Disabled	ENGO OFF
Day 2	OFF	Enabled	ENGO ON with default setpoint
Day 3	**ON**	Disabled	ENGO OFF
Day 4	**ON**	Enabled	ENGO ON with default setpoint
Day 5	**ON**	Enabled	ENGO ON with dispatched setpoint

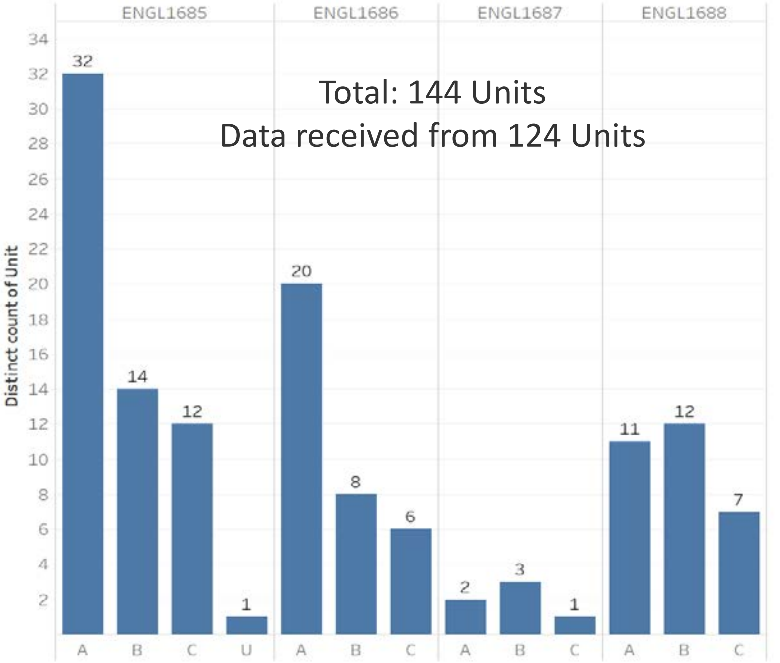
Field Data Collection and Analysis



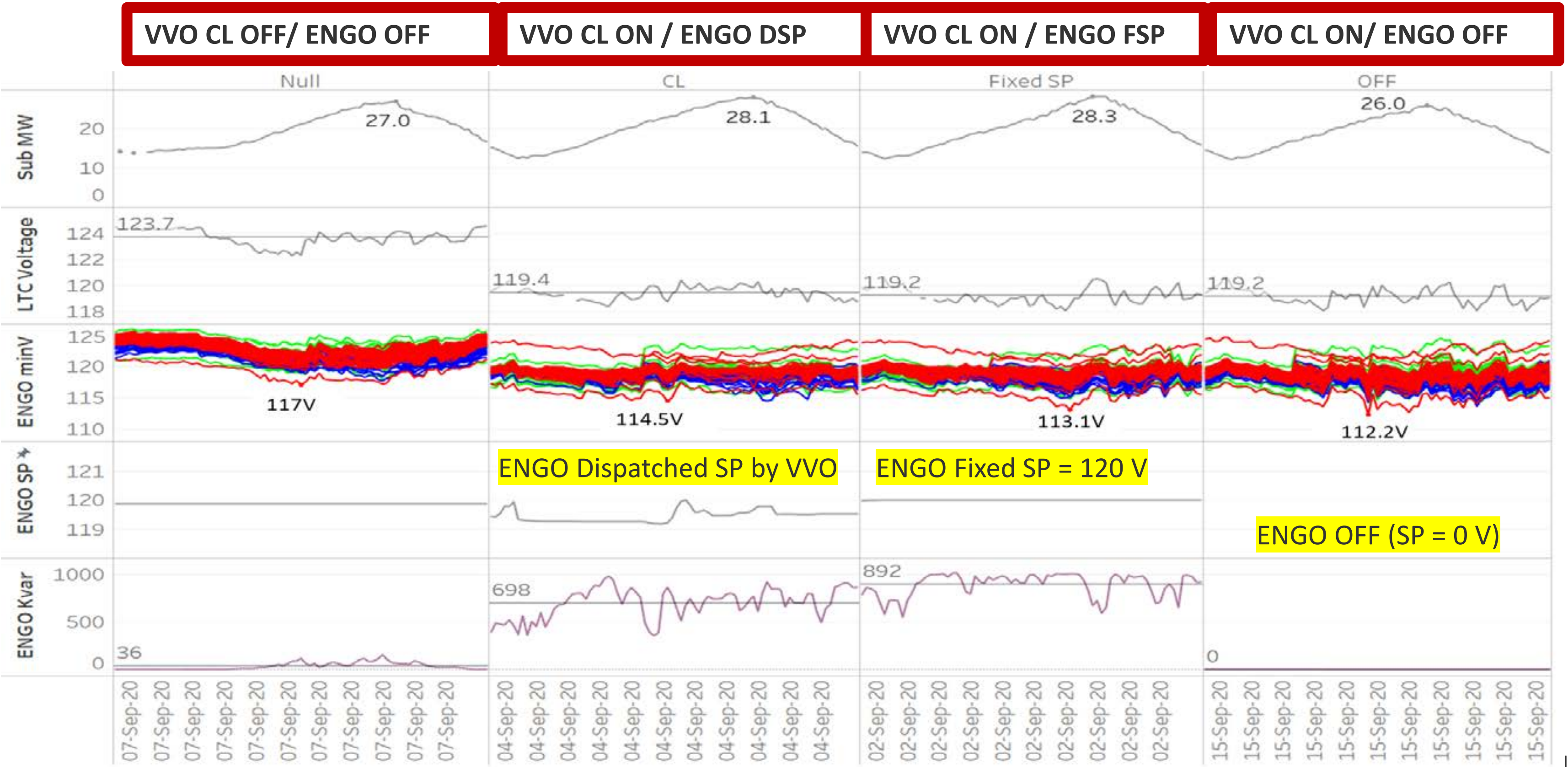
Field Data Collection and Analysis

Voltage Boost	ENGL 1685	ENGL 1686	ENL 1687	ENGL 1688
Phase A	1.6 V	1.1 V	0.5 V	1.1 V
Phase B	1.0 V	1.5 V	0.1 V	1.2 V
Phase C	1.9 V	1.2 V	0.6 V	1.8 V

ENGO deployment based on the data shared



Field Data Collection and Analysis



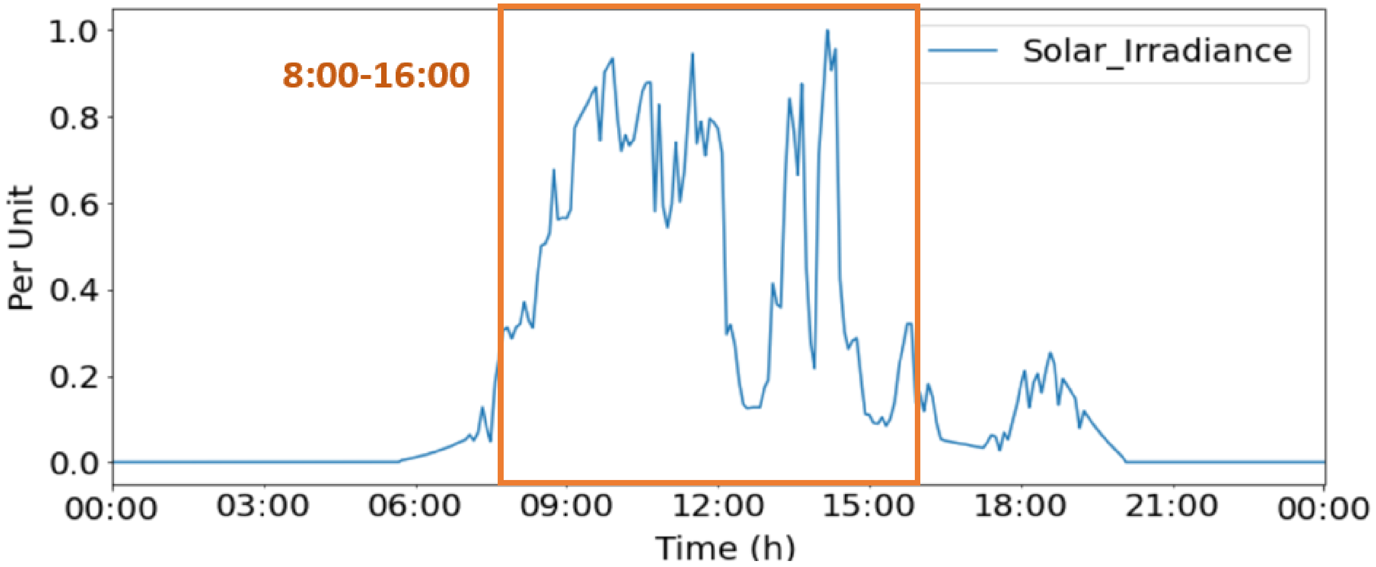
Updating HIL models with field data and demonstrating PV control

Simulation Scenarios

- Baseline: Legacy assets operate in local control mode, no ENGOs
- S2: RTOPF issues setpoints to PV smart inverters

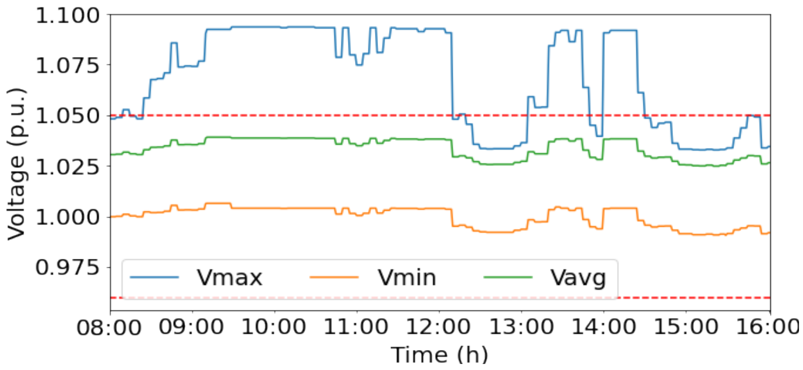
Scenario	Legacy devices	ENGO units	PV smart inverters
Baseline	Local control	×	Unity power factor
S2	ADMS	ADMS	RTOPF

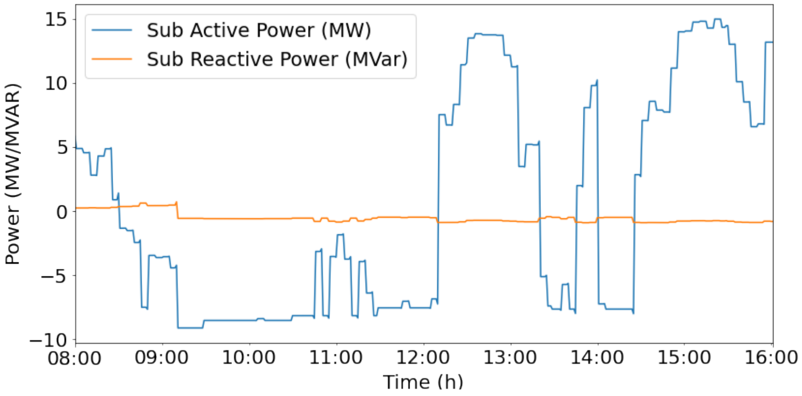
HIL Testing Results – Baseline Scenario

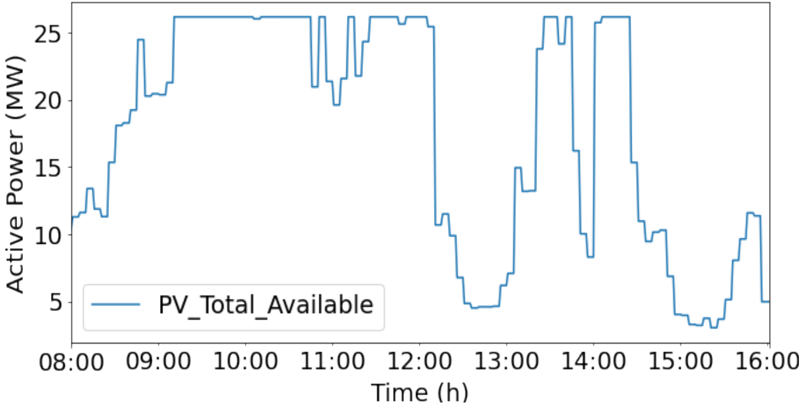


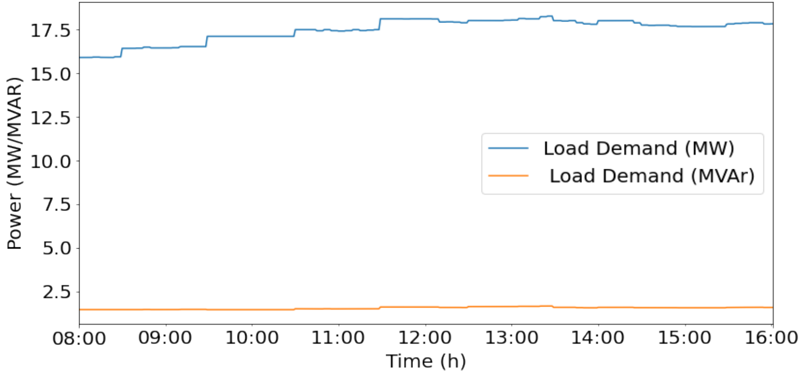
- High PV scenario with highly fluctuating solar irradiance
- ADMS is disabled, legacy devices operate in autonomous mode (LTC TAP position 0 and Capacitor banks closed), ENGOs are disabled, and PVs operates in unity power factor mode

HIL Testing Results – Baseline Scenario

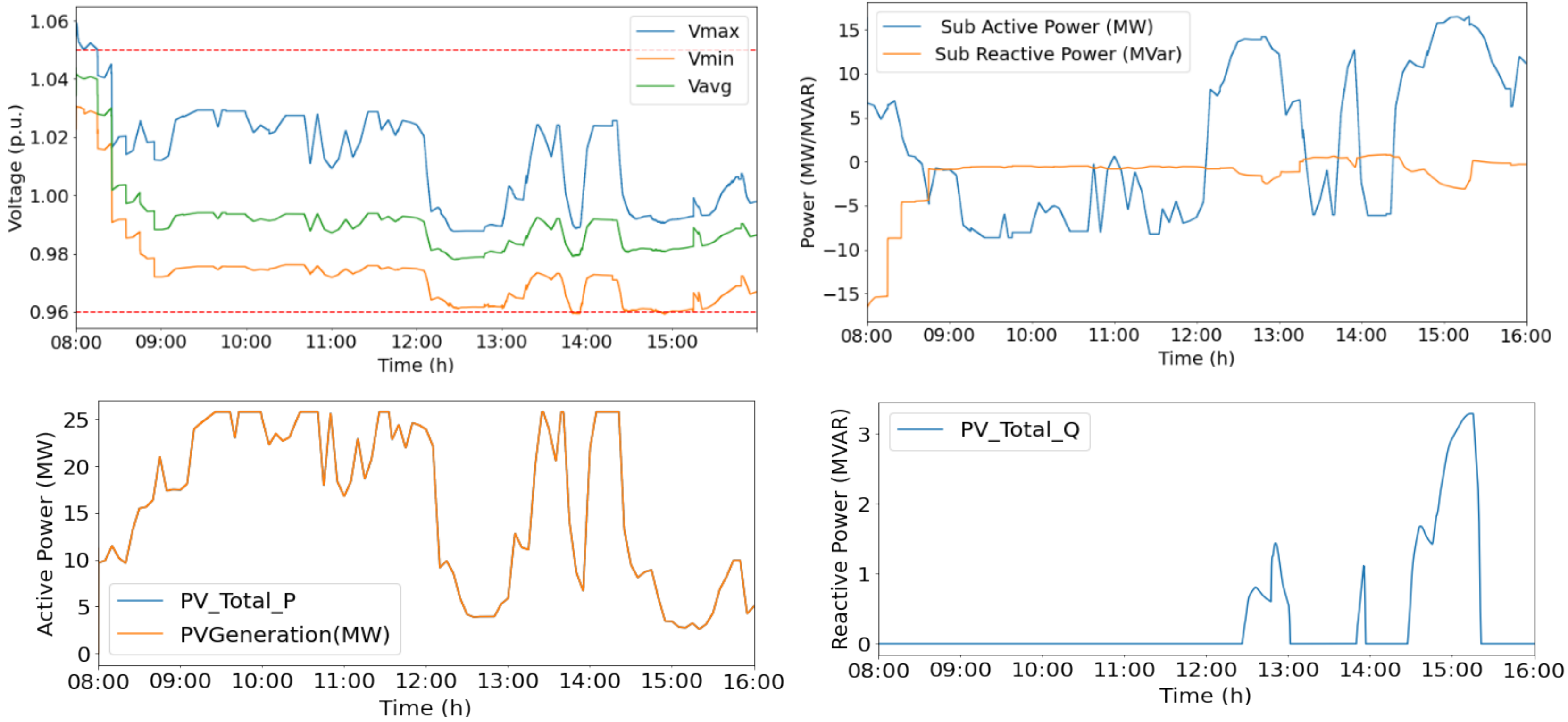








HIL Testing Results with PV control



- **System voltages are regulated within the target limits (0.95-1.05 p.u.)**
- **No curtailment in PV and reactive power is injected to improve the voltages**

HIL Testing Results with PV Control

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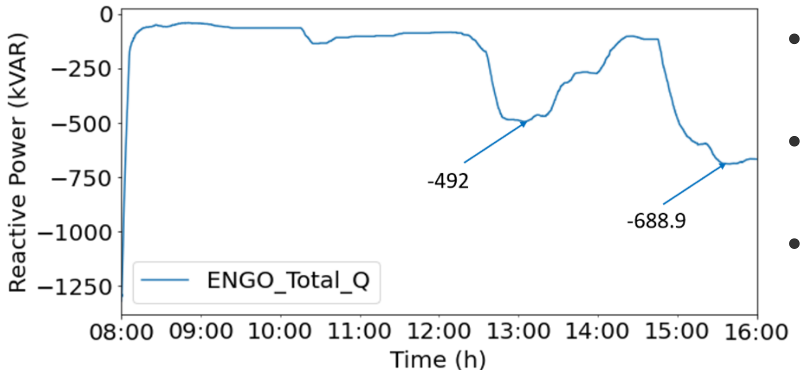
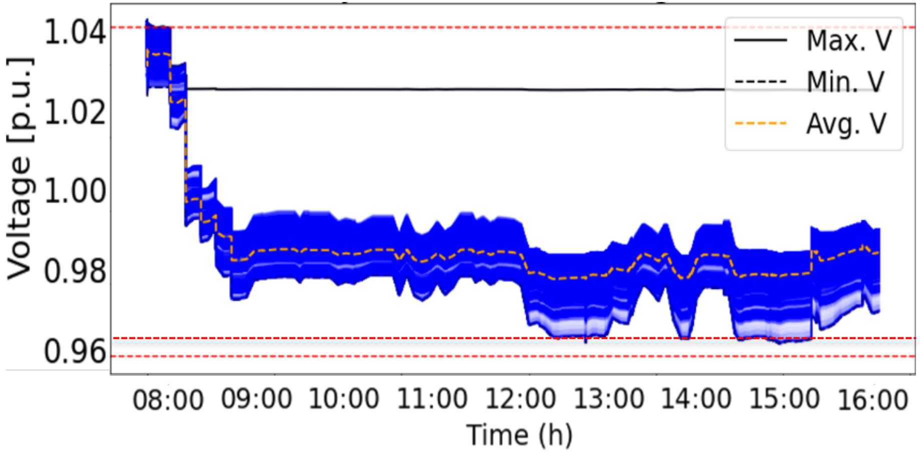
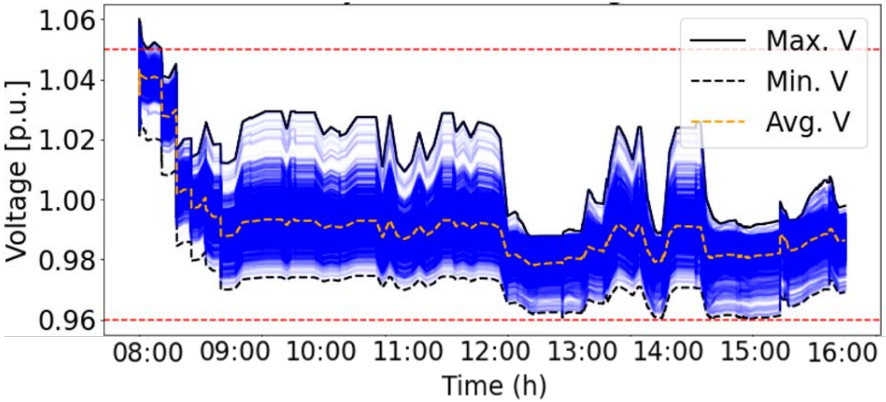


- ENGOs contribute reactive power during the low solar irradiance periods
- System medium voltages are regulated above the target limits (0.967-1.05 p.u.)
- System low voltages are regulated within 0.96-1.05 p.u.

System Medium Voltages (Primary side 12.47 kV)



System Low Voltages (Secondary side 120 V)



Summary of Testing Results

Scenario	Energy delivered (MWh)	Energy savings (MWh)	Energy savings (%)	PV curtailment (%)	Voltage Exceedances (node-hours)*
Baseline	143.853	N/A	N/A	0%	3178
PHIL Test #1	140.3014	3.551637	2.780616	0%	11.8
PHIL Test #2	140.6606	3.192362	2.468935	0%	13.5

*node-hours: sum of nodes multiplied by time in-hour exceeding voltage thresholds (0.95pu-1.05pu)

Techno-Economic Analysis

Techno-economic Analysis

Scenario	PV penetration	Legacy Devices	ENGO units	PV inverters
Baseline	Low PV	Local control	×	Unity power factor
Baseline	High PV	Local control	×	Unity power factor
S1	High PV	ADMS	ADMS	Local volt-var-watt control mode
S2	High PV	ADMS	ADMS	RTOPF

- Metrics: PV curtailment, upgrade costs , CVR benefits
- Baseline costs:
  - Cost of implementing equipment and operational upgrades to mitigate voltage excursions caused by PV.
  - NREL is setting up the DISCO tool for this project.
- Advanced control costs
  - Prorated ADMS cost + 144 ENGOs + upgraded LTC control + 18 primary capacitor banks

Flow for Calculating Impacts

Models of technology components and controls

↕

Quasi-static time-series (QSTS) power flow simulations

↓

Code to post-process OpenDSS results and report annual curtailment, energy losses, and number of device operations

Challenge:

- Cannot do full 1-year QSTS simulations with the ADMS
- Typically use full 1-year analysis because at least one year is needed to give confidence in curtailment estimates and number of device operations
- **Alternative approaches and understanding sensitivity to running a few specially selected days and extrapolating versus 1-year**

DISCO Analysis – High PV Baseline

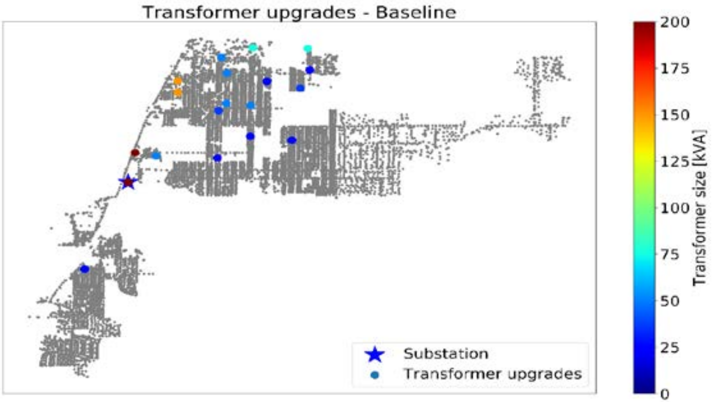
- Baseline upgrade costs: transformers, lines, change settings, etc.
- Two phases
  - Thermal violations
    - Added 22 transformers with higher kVA capacity
    - From 297 buses with violations to zero
  - Voltage violations
    - Changed capacitor and regulator settings in two locations
    - From 220 buses with violations to 108
    - DISCO's solution can't converge beyond 108

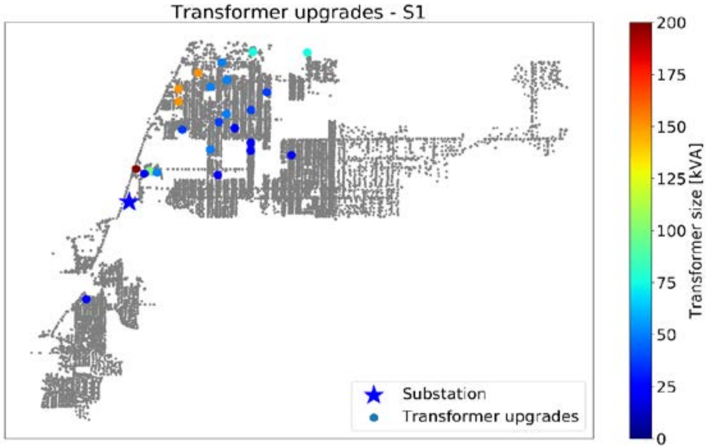
Costs for S1 & S2 scenarios

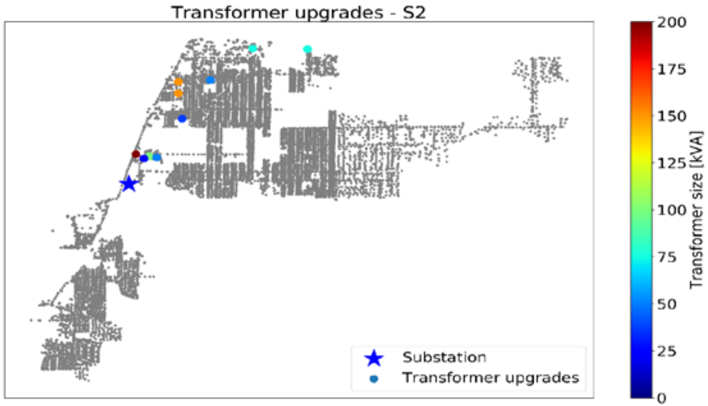
- GEMS + ADMS (prorated) + ENGOs + Other devices (regulators, etc.)
- Prorate factor
  - $\frac{Annual\ energy\ consumption\ in\ Engl\ feeders}{(Annual\ energy\ Xcel\ sales\ in\ CO)}$=0.56%
- ADMS utilization factor
  - 30%, recognizes that ADMS has multiple uses/benefits for Xcel

Techno-Economic Analysis

- Clockwise (starting on the right):
  - Baseline (high PV; no ADMS/GEMS/PV control
  - S1 (ADMS + GEMS + Volt-VAr-Watt control for PV)
  - S2 (ADMS + GEMS + DERMS)







Project Key Outcomes and Impacts

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- Validated novel hybrid control architecture
- Reliable and secure grid operation for high PV grids
- Interoperable interfaces for integration of system-level controls on the Utility Enterprise Bus
- Laboratory and field validation of hierarchical controls
- Techno-economic analysis to quantify cost-benefits for different scenarios
- Dissemination and feedback from Industry Advisory Board (IAB) with over 40 industry members

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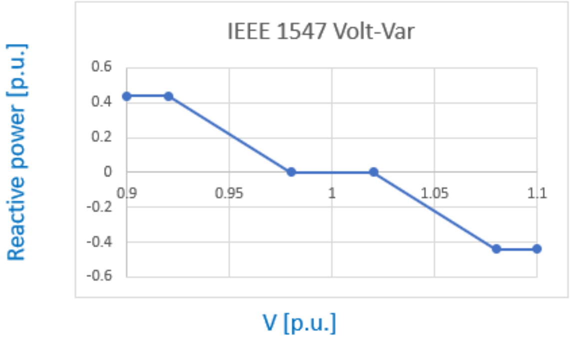
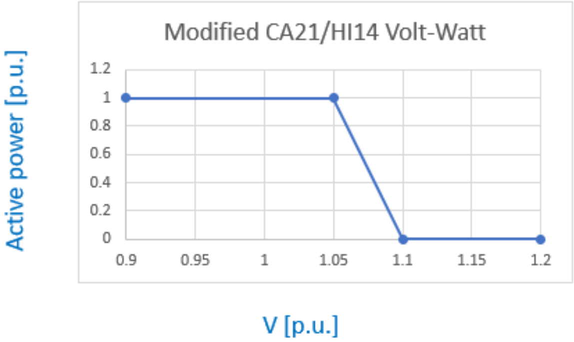
Backup - cybersecurity

PV Inverter Control in S1

- Volt-VAR-Watt control is used for all PV inverters in S1.
- In this mode, the PV inverters follow the volt-var curve shown in the figure to determine the reactive power injection/absorption. If there is not sufficient inverter capacity, the active power will be curtailed to free up the capacity to inject the reactive power; reactive power is prioritized.



Volt-VAR curve recommended by IEEE 1547



Modified CA21/HI14 Volt-WATT curve

Technical Accomplishments – Cybersecurity Evaluation

Cybersecurity Evaluation Plan

1. Packet Capture Analysis
2. Vendor Device Analysis
3. NREL Device Security Analysis