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 <10 sec, 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
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.
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)

- Unique contribution of our team [Dall’Anese at al’14, Bernstein at al’14]
- Real-time (second level)
- Modular
- Distributed
- Stable
- Optimal

Network Optimized Distributed Energy Systems (NODES)
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

Grid Edge Voltage Regulation

ADMS VVWO
- Data Acquisition
- Distribution System Model
- Control Decision Making

Distributed PV Inverter Control using RT-OPF

DEHC Architecture

Control Assets
- ENGO
- LTC
- Voltage Regulator
- Switchable Capacitor
- PV Inverter

System under control

Distribution Level

Primary Distribution
- ADMS controls for legacy devices

Secondary Distribution
- GEMS-based central control
- ADMS control for PV inverters

Control Time Period
- RT-OPF
- 1 sec
- 10 sec
- 100 sec
- 1000 sec

SCADA measurements

Control
DEHC Controls Exchange

Varentec

Coordination between ADMS and GEMS

GEMS-based Central Control

ENG0-based Local Control

Schneider

ADMS-based Central Control

ADMS-issued PV Inverter Setpoints

RT-OPF-based Distributed Control for PV Inverters

NREL

Inverter-based Local Control
HIL Implementation Using ADMS Test Bed

ADMS Test Bed Implementation for ECO-IDEA

Co-simulation platform
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

- ADMS user interface
- OPAL-RT Real-time simulator
- Power and controller hardware
- ADMS user interface

Test bed coordinator

Varentec user interface

OpenDSS & DERMS

Grid-Edge Devices
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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Legacy devices</th>
<th>ENGO units</th>
<th>PV smart inverters</th>
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<tbody>
<tr>
<td>Baseline</td>
<td>Local control</td>
<td>×</td>
<td>Unity power factor</td>
</tr>
<tr>
<td>S1</td>
<td>ADMS</td>
<td>ADMS</td>
<td>Local volt/var control mode</td>
</tr>
<tr>
<td>S2</td>
<td>ADMS</td>
<td>ADMS</td>
<td>RTOPF</td>
</tr>
</tbody>
</table>
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)
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**

Substation demand (MW)

**PV generation**

PV Generation (MW/Mvar)

**Voltage distribution**

Min/Max voltages

Voltage profile at Vmax time step

Voltage profile at Vmin time step

Voltage distribution

S2 Case
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

• 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 controls legacy devices

ADMS coordinates with RT-OPF DERMS

ADMS controls grid-edge devices

Co-simulation platform

ADMS Test Bed Implementation for ECO-IDEA
HIL Test Results

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

ADMS-centered operation HIL test

Measured voltages - baseline
Measured voltages - HIL

Extreme voltages - baseline
Extreme voltages - HIL

Voltage [p.u.]
Voltage [p.u.]

Time [hours]
Time [hours]

Max. V
Min. V
Avg. V
Max. V
Min. V
Avg. V
The RTOPF algorithms (coordinator and local controllers) converge and work as expected to regulate system voltages.
Taking DEHC to the field
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

- 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

<table>
<thead>
<tr>
<th>One testing cycle</th>
<th>VVO CL status</th>
<th>ENGOs status</th>
<th>ENGOs setpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>OFF</td>
<td>Disabled</td>
<td>ENGO OFF</td>
</tr>
<tr>
<td>Day 2</td>
<td>OFF</td>
<td>Enabled</td>
<td>ENGO ON with default setpoint</td>
</tr>
<tr>
<td>Day 3</td>
<td>ON</td>
<td>Disabled</td>
<td>ENGO OFF</td>
</tr>
<tr>
<td>Day 4</td>
<td>ON</td>
<td>Enabled</td>
<td>ENGO ON with default setpoint</td>
</tr>
<tr>
<td>Day 5</td>
<td>ON</td>
<td>Enabled</td>
<td>ENGO ON with dispatched setpoint</td>
</tr>
</tbody>
</table>
Field Data Collection and Analysis

VVO CL ON / ENGO DSP
VVO CL ON / ENGO FSP
VVO CL ON / ENGO OFF

ENGO SP controlled by VVO
ENGO SP = 120 V
ENGO OFF (SP = 0 V)
## Field Data Collection and Analysis

<table>
<thead>
<tr>
<th>Voltage Boost</th>
<th>ENGL 1685</th>
<th>ENGL 1686</th>
<th>ENL 1687</th>
<th>ENGL 1688</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phase A</strong></td>
<td>1.6 V</td>
<td>1.1 V</td>
<td>0.5 V</td>
<td>1.1 V</td>
</tr>
<tr>
<td><strong>Phase B</strong></td>
<td>1.0 V</td>
<td>1.5 V</td>
<td>0.1 V</td>
<td>1.2 V</td>
</tr>
<tr>
<td><strong>Phase C</strong></td>
<td>1.9 V</td>
<td>1.2 V</td>
<td>0.6 V</td>
<td>1.8 V</td>
</tr>
</tbody>
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ENGO deployment based on the data shared

Total: 144 Units
Data received from 124 Units
Field Data Collection and Analysis

**VVO CL OFF/ ENGO OFF**
- ENGO Dispatched SP by VVO
- ENGO Fixed SP = 120 V
- ENGO OFF (SP = 0 V)

**VVO CL ON / ENGO DSP**
- CL 28.1

**VVO CL ON / ENGO FSP**
- Fixed SP 28.3

**VVO CL ON/ ENGO OFF**
- OFF 26.0
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

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</table>
• 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

- 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.
## Summary of Testing Results

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

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

- **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
  \[
  \text{Prorate factor} = \frac{\text{Annual energy consumption in Engl feeders}}{\text{Annual energy Xcel sales in CO}} = 0.56\%
  \]
- 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

- 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
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
Cybersecurity Evaluation Plan

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