NREL

Utility and Grid Operator Resources for Future Power Systems Webinar Series

Virtual Power Plants and Distributed Energy Resource Management Systems

Harsha Padullaparti, Ph.D.
Senior Researcher, NREL

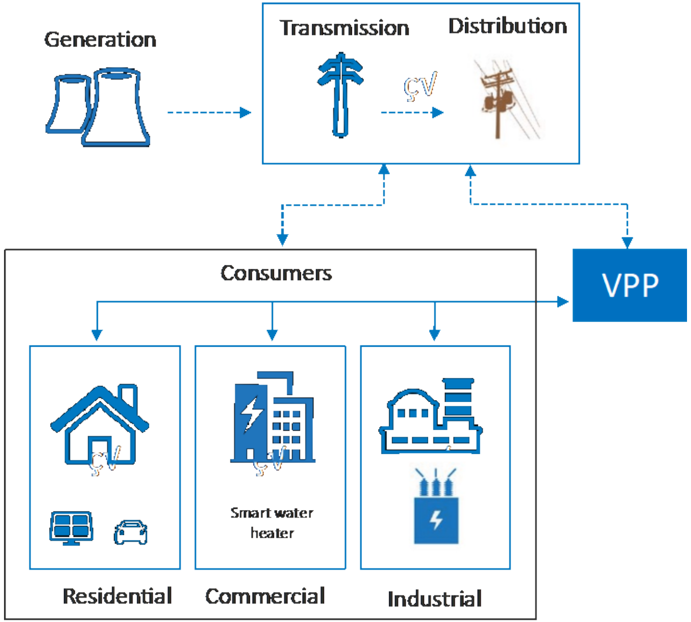
NREL Webinar Series
July 15, 2025

Contents

What is a VPP?

- Virtual Power Plants (VPP) are aggregations of distributed energy resources (DERs) that can balance electrical loads and provide utility-scale and utility-grade grid services **like a traditional power plant**.

- Distributed Energy Resources (DER):
  - Utility-scale photovoltaic (PV), battery energy storage system, flexible commercial and industrial loads, etc.
  - Behind-the-meter: Residential electric vehicle (EV), battery energy storage system, electric water heaters, HVAC controls, smart buildings, etc.
  - Can be grouped into demand, generation, and storage



VPP State-of-the-Art

- Between 2023 and 2030, the United States will need to add enough new generation capacity to supply **~200 GW*** of peak demand growth.
- Depending on how VPP is defined, **30–60 GW (<10%)** of peak demand is served by VPPs to date.
  - Peak demand served by VPP is expected to grow to **80–160 GW** by 2030 to serve **10–20%** of peak demand (∼**3x** present levels).
- VPPs are not new and in operation for years in the form of demand response programs. While demand response programs like TOU rates influence customer behavior indirectly, VPPs actively control/manage and dispatch DERs.
- Example DER roles in VPP:

  Demand
  - *Smart thermostats:* Buildings/homes can be preheated, precooled to shift demand
  - *Smart water heaters:* Heat pump/resistive water heaters can be controlled to preheat water during off-peak hours

  Generation
  - PVs: VPPs aggregate multiple distributed PV systems to deliver sufficient generation capacity, offsetting peak loads

  Storage
  - *EV chargers:* Charging rates adjusted to shift demand, can perform vehicle to X
  - *Behind the meter batteries:* Charged when price is low and discharged when price is high, provide back-up power during outages

https://www.energy.gov/lpo/articles/doe-releases-new-report-pathways-commercial-liftoff-virtual-power-plants

VPP Services

Grid Service	VPP Contribution
Resource Adequacy	Aggregate DERs to ensure sufficient supply during peak periods, reducing reliance on peaker plants.
Cost Reduction	Optimize dispatch of low-cost resources (e.g., PV, batteries), reducing investment and fuel costs.
Reliability & Resilience	Coordinate distributed resources across geographies; maintain service during outages or disturbances.
Islanding Capability	Enable microgrid operation using local DERs during grid outages, ensuring critical load support.

Distributed Energy Resources Management System

A software platform to assist utilities in managing the grid operation with the support of distributed energy resources assets

- Manage device information
- Monitor
- Aggregate
- Control
- Ancillary services

- Value delivered by DERMS
  - Enhances situational awareness to accelerate renewable integration and provide grid flexibility.
  - Defers expensive grid upgrades by offering non-wires alternatives.
  - Improves system reliability through coordinated DER control and operational flexibility.

DERMS Capabilities

DER Device Management	DER Monitoring, Control & Analysis	Grid Services	Market
Registration	Forecasting	Energy, Capacity, Constraint Management	Bidding, Settlement
Asset Modeling	Aggregation	Power Quality	Transactive Energy
Data Exchange	Scheduling & Dispatch	VVO	
	VPP	Resilience	
	Demand Response		

https://sepapower.org/resource/encyclopedia-of-derms-functionalities/

Federal Energy Regulatory Commission (FERC) Order 2222

- FERC Order 2222 facilitates participation of DERs in regional electricity markets through aggregators/virtual power plants (VPPs)
- Before this order, VPPs were largely excluded from these markets due to lack of market structures and regulations
- As of March 2024, the California Independent System Operator has received full approval for its compliance plan. Other regional transmission organizations and independent system operators—including the Midcontinent Independent System Operator, the New York Independent System Operator, PJM Interconnection, ISO New England, and the Southwest Power Pool—have submitted their respective plans and are in various stages of ongoing implementation.

Goals

- Wholesale market access for DER Aggregators/VPPs
- Equal Footing: VPPs treated comparably to traditional power plants
- Enhanced grid flexibility and resilience
- Lower consumer costs, renewable integration
- promote innovation and competition

Stakeholders

- FERC
- Independent System Operators (ISOs) and Regional Transmission Operators (RTOs)
- Distribution Utilities
- Aggregators
- State regulators
- Consumers
- Equipment manufacturers
- Software vendors

Key Challenges

- Coordination across Transmission, Distribution and customer domains
- Lack of distribution system visibility for ISOs and RTOs
- Data Sharing: Establishing protocols for effective data sharing among stakeholders
- Integrating DERs into resource, distribution, and transmission planning

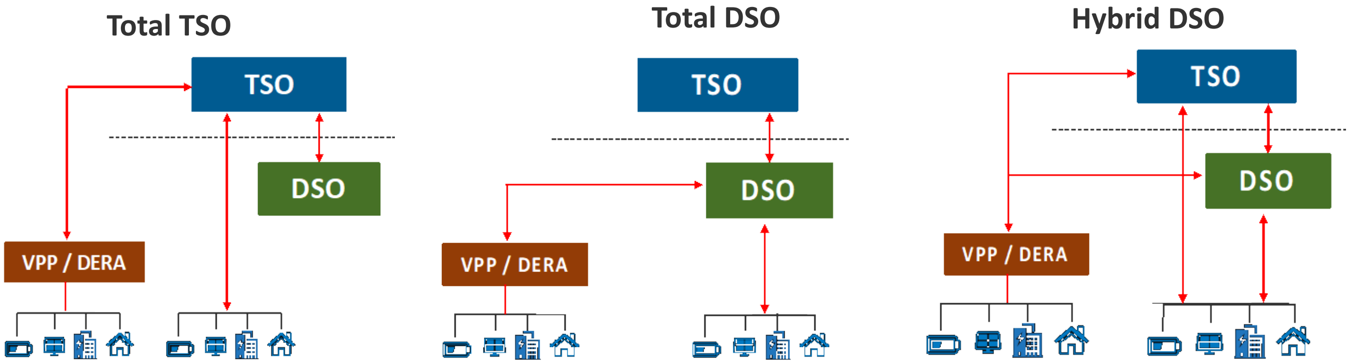
Zhou, Ella, David Hurlbut, and Kaifeng Xu. 2021. *A Primer on FERC Order No. 2222: Insights for International Power Systems*. Golden, CO: National Renewable Energy Laboratory. NREL/ TP-5C00-80166. https://www.nrel.gov/docs/fy21osti/80166.pdf

Grid Architectures

- **Total Transmission System Operator:** TSO (ISO/RTO) coordinates both transmission-level operations and DER participation. VPPs/DER aggregators (DERAs) interact directly with TSO.
  - TSO's limited visibility to distribution -> operational conflicts.

- **Total Distribution System Operator:** DSO acts as intermediary between VPP and TSO coordinating VPP's market participation ensuring local grid stability.
  - Requires advanced operational capabilities and market knowledge at DSO level.

- **Hybrid DSO:** Shared responsibilities between TSO and DSO for effective DER aggregation and grid stability.
  - Requires robust coordination mechanisms between TSO and DSO. Potentially more complex regulatory and technical frameworks.



Annabelle Pratt. 2023. "Autonomous Energy Systems Functional Interoperability." Presented at NREL Autonomous Energy Systems Workshop; Golden, CO. July 2023. URL: https://www.nrel.gov/docs/fy23osti/86851.pdf

NREL ADMS Test Bed

The **advanced distribution management system (ADMS)** is a utility-operated platform focusing on grid operations and reliability. The **DERMS** manages DERs, and **VPPs** aggregate DERs to participate in energy markets.

ADMS test bed capabilities for VPP evaluations:

- Multi-time scale cosimulation using Hierarchical Engine for Large-scale Infrastructure Co-Simulation (Open Distribution System Simulator/OPAL-RT/Real-Time Digital Simulator)
- Hardware integration
- Communications interfaces
- Data collection and visualization

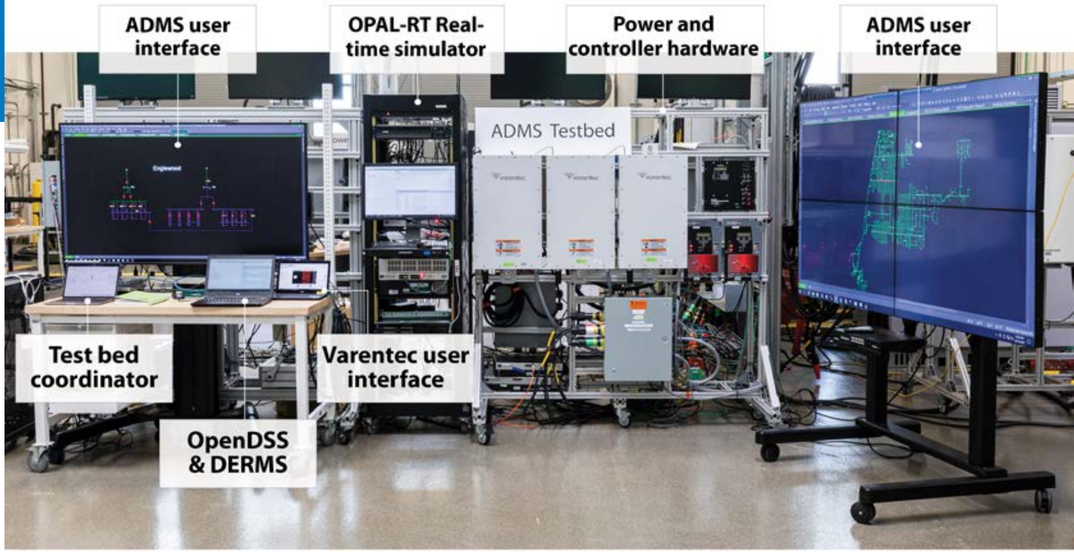
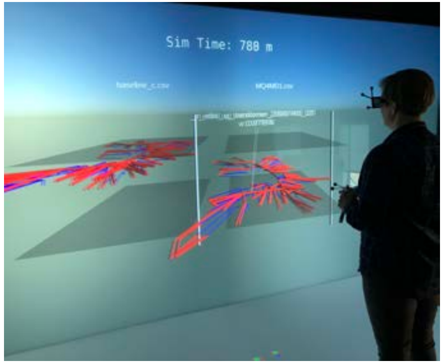


Image Sources: NREL

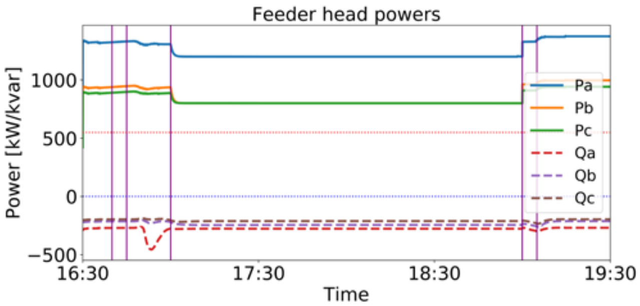
2D real-time visualization

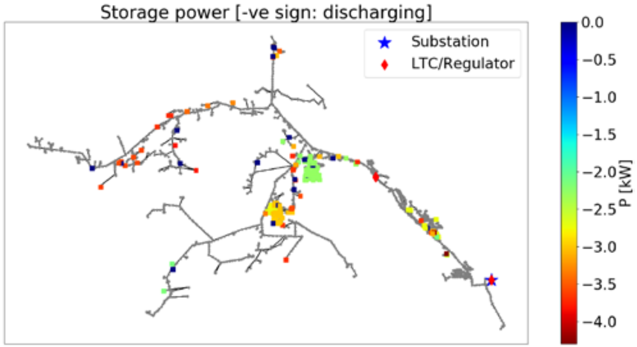


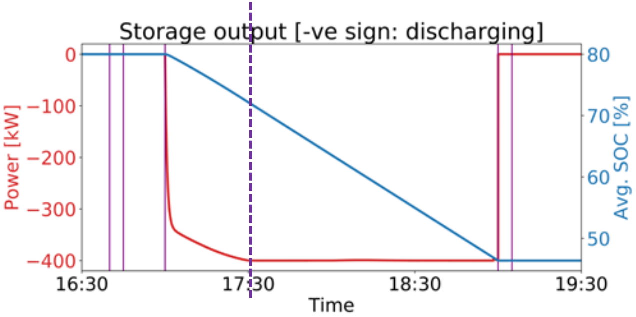
3D visualization

Peak Demand Management using VPP

- VPP implemented in Holy Cross Energy (HCE)'s distribution system
- DERMS Peak Load Management target powers: 1200 kW, 800 kW, and 800 kW



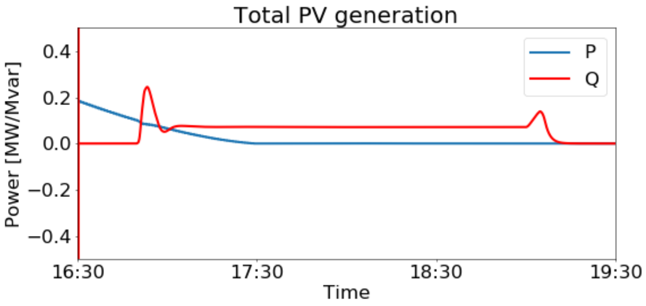


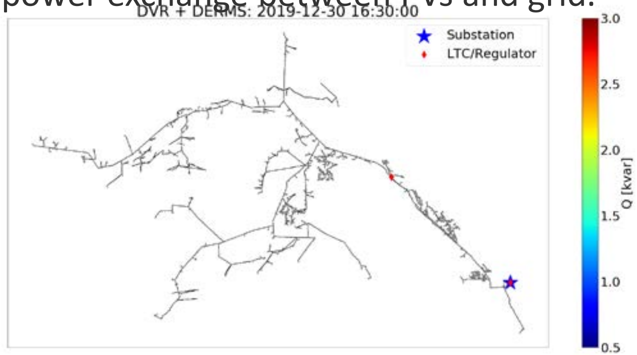


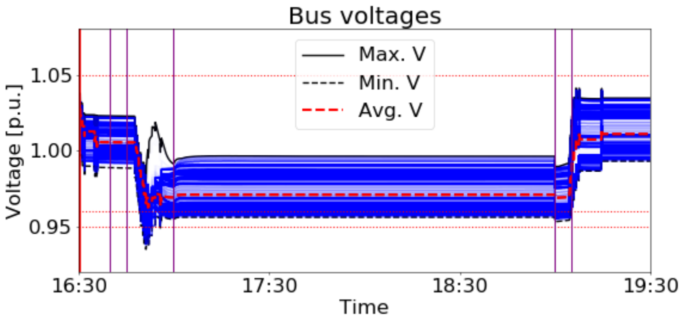
Connor O'Neil. 2019. "Small Colorado Utility Sets National Renewable Electricity Example Using NREL Algorithms." NREL. Dec. 10, 2019. URL: https://www.nrel.gov/news/features/2019/small-colorado-utility-sets-national-renewable-electricity-example-using-nrel-algorithms.html

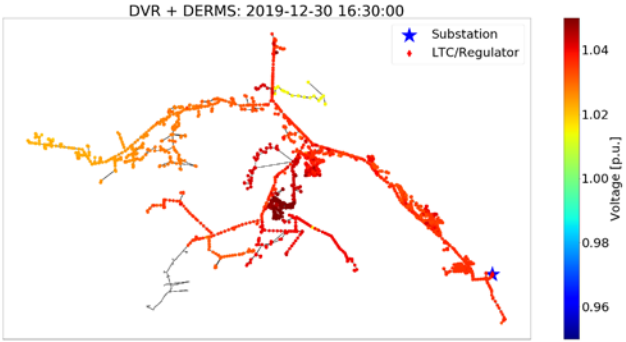
Padullaparti, Harsha, Annabelle Pratt, Ismael Mendoza, Soumya Tiwari, Murali Baggu, Chris Bilby, and Young Ngo. "Peak Demand Management and Voltage Regulation Using Coordinated Virtual Power Plant Controls." IEEE Access 11, 130674–130687. URL: https://www.nrel.gov/docs/fy24osti/81105.pdf

- Dynamic voltage regulation (DVR) performs conservation voltage reduction (CVR) by reducing voltages, DERMS voltage regulation ensures the bus voltages are above 0.95 p.u., DERMS VPP dispatches BESS powers to ensure power tracking at the substation.
- The dynamic voltage regulation (DVR) is enabled at 16:45, DERMS voltage regulation enabled at 16:40, and the DERMS VPP is enabled at 17:00.
- At time 16:30, the system voltages are higher. No reactive power exchange between PVs and grid.



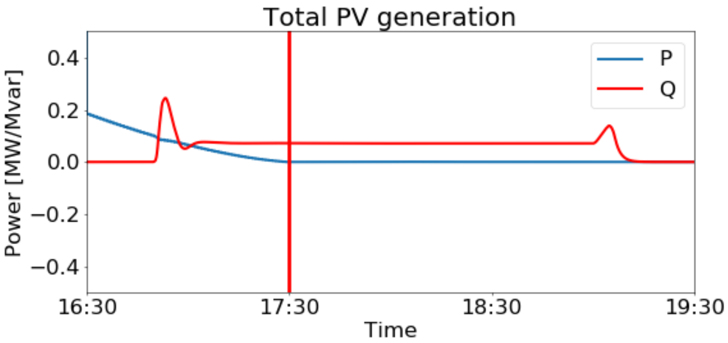


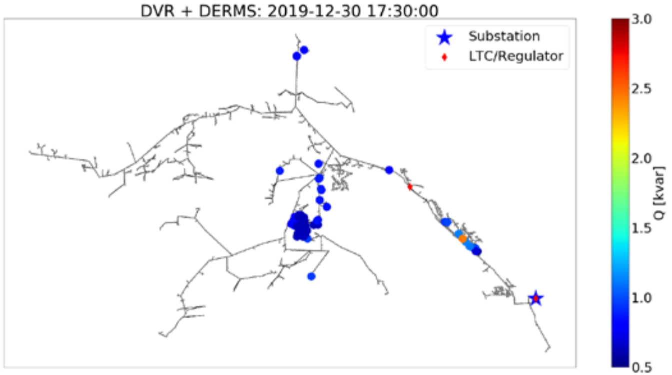


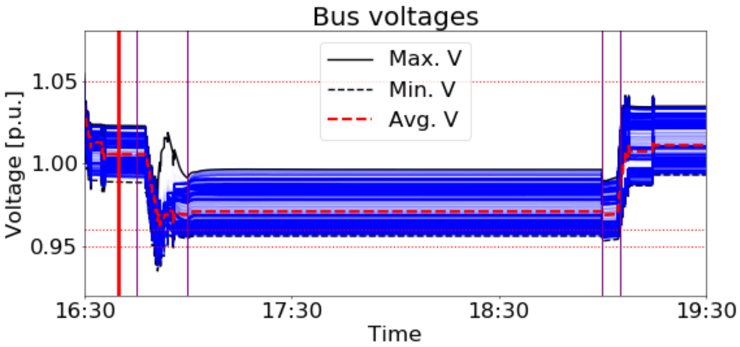


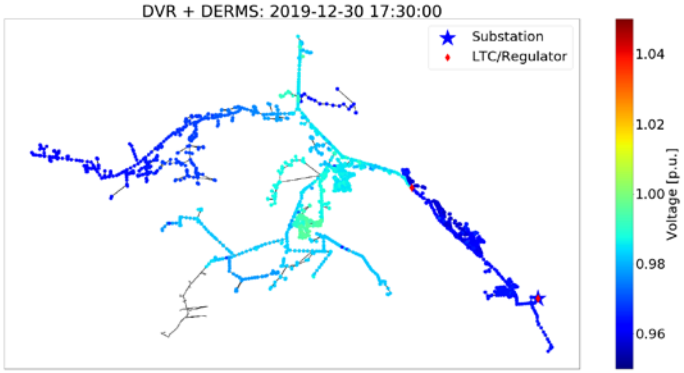
Padullaparti, Harsha, Annabelle Pratt, Ismael Mendoza, Soumya Tiwari, Murali Baggu, Chris Bilby, and Young Ngo. "Peak Demand Management and Voltage Regulation Using Coordinated Virtual Power Plant Controls." IEEE Access 11, 130674–130687. URL: https://www.nrel.gov/docs/fy24osti/81105.pdf

- At time 17:30, the system voltages are already lowered by the DVR (enabled at 16:45) to reduce the demand through conservation voltage reduction.
- DERMS dispatching PV smart inverters to export reactive power to the grid to ensure voltages do not go below 0.95 p.u.



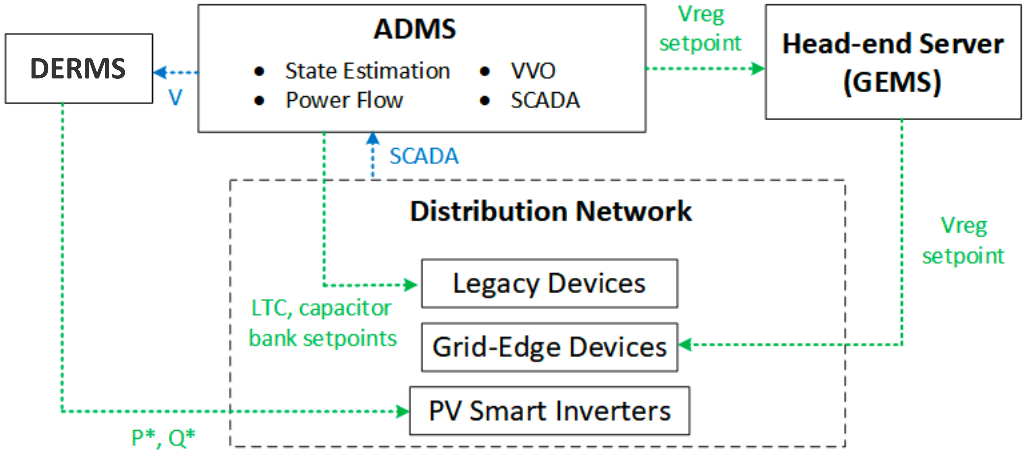


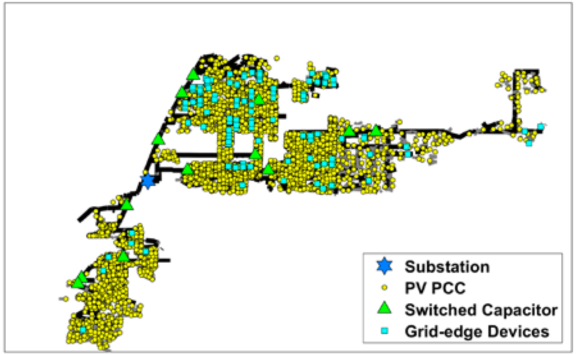




Padullaparti, Harsha, Annabelle Pratt, Ismael Mendoza, Soumya Tiwari, Murali Baggu, Chris Bilby, and Young Ngo. "Peak Demand Management and Voltage Regulation Using Coordinated Virtual Power Plant Controls." IEEE Access 11, 130674–130687. URL: https://www.nrel.gov/docs/fy24osti/81105.pdf

Grid Management with ADMS, DERMS, and Grid-Edge Controls





Distribution grid with high-PV

VVO: Volt/VAR Optimization
SCADA: Supervisory Control and Data Acquisition
GEMS: Grid Energy Management Systems
LTC: Load Tap Changer

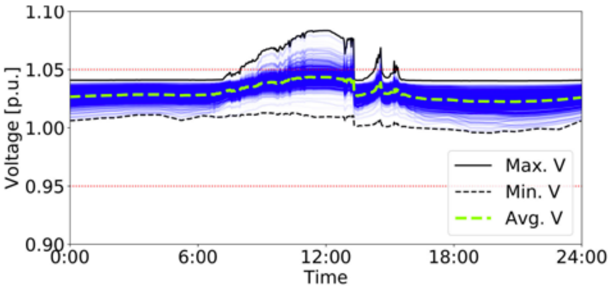
- Padullaparti, Harsha, Jing Wang, Santosh Veda, Murali Baggu, and Anastasios Golnas. 2022. "Evaluation of Data-Enhanced Hierarchical Control for Distribution Feeders With High PV Penetration." *IEEE Access* 10: 42860–42872. URL: https://doi.org/10.1109/ACCESS.2022.3168131.
- Strezoski, Luka, Harsha Padullaparti, Fei Ding, and M. Baggu. 2022. "Integration of Utility Distributed Energy Resource Management System and Aggregators for Evolving Distribution System Operators." *Journal of Modern Power Systems and Clean Energy* 10(2): 277-285. URL: https://doi.org/10.35833/MPCE.2021.000667.
- Wang, Jing, Harhsa Padullaparti, Fei Ding, Murali Baggu, and Martha Symko-Davies. 2021. "Voltage Regulation Performance Evaluation of Distributed Energy Resource Management via Advanced Hardware-in-the-Loop Simulation." MDPI Energies 14(20): 17–20. URL: https://doi.org/10.3390/en14206734.

Grid Management with ADMS, DERMS, and Grid-Edge Controls

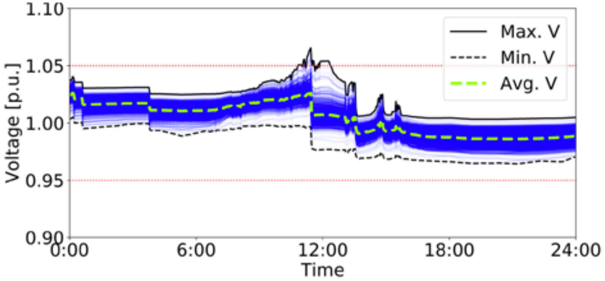
Simulation Scenarios

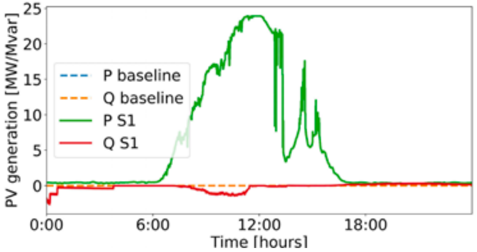
Scenario	Legacy devices	Grid-edge devices	Smart inverters
Baseline	Local control	Disabled	Unity power factor operation
S1	Controlled by the ADMS	Controlled by the GEMS/ADMS	Local control, follow Volt-VAR control curve
S2	Controlled by the ADMS	Controlled by the GEMS/ADMS	Follow RTOPF issued P, Q set points

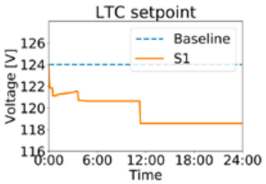
Baseline

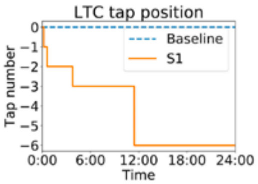


S1: ADMS control enabled

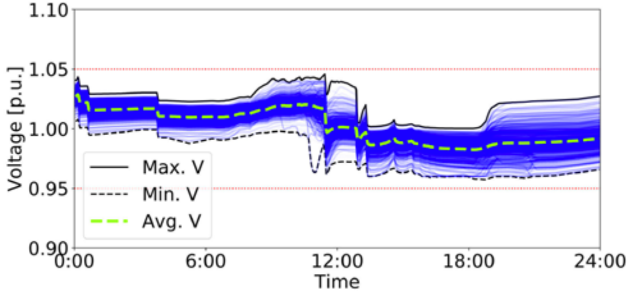


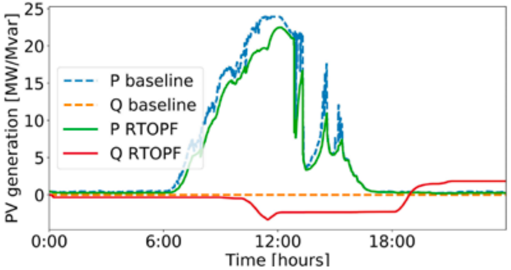






S2: ADMS + DERMS controls enabled





Padullaparti, Harsha, Jing Wang, Santosh Veda, Murali Baggu, and Anastasios Golnas. 2022. "Evaluation of Data-Enhanced Hierarchical Control for Distribution Feeders With High PV Penetration." *IEEE Access* 10: 42860–42872. URL: https://doi.org/10.1109/ACCESS.2022.3168131.

Prime Time VPP and GRid Integration and Demonstration of FLEXible Energy Resources (GRID-FLEXER)

- **Xcel Energy** plans to develop and integrate a VPP in Boulder, Colorado.
- *Key Drivers:* Boulder's research labs, University of Colorado Boulder, advanced tech companies. Rapid electrification of customer end uses.
- VPP will be used to balance, optimize, and shift electrical loads, minimizing upgrades and costs for customers without building new power plants/transmission lines.

- **Dominion Energy Virginia** plans to demonstrate a DERMS to coordinate diverse DERs like solar, batteries, EVs, and smart appliances in Southeastern Virginia.
- Aims to optimize 150 MW of clean energy to provide real-time grid support avoiding costly grid infrastructure investments.
- Pave the way for wider implementation across Dominion Energy Virginia's service territory and beyond.

"Distributed Energy Systems Demonstrations Program". U.S. Department of Energy, Office of Clean Energy Demonstrations. [Online]. Available: *https://www.energy.gov/sites/default/files/2024-11/FINAL%20DES%20National%20Briefing%20Slides.pdf*

IEEE 1547-2018, 1547.3: Enabling Communication for VPPs

1. **Standardized Communication**:
   1. Enables VPP platforms to coordinate diverse DERs, such as solar, batteries, and EVs
   2. Supports real-time data exchange for monitoring and control

2. **Interoperability**:
   1. Promotes compatibility across various DER technologies and manufacturers
   2. Simplifies the integration of new resources into existing VPPs

3. **Grid Responsiveness**:
   1. Aligns DER operations with grid requirements
   2. Enhances VPP performance during demand peaks, contingencies, and grid balancing events

IEEE. 2018. "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces." IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003) 1–138. URL: https://doi.org/10.1109/IEEESTD.2018.8332112.

VPP Implementation Barriers/Roadmap

Technical Requirements	
Hardware	DERs, Smart meters
Software	DER aggregation algorithm, demand and generation forecasting models
Communication Protocols	Interoperable protocols for co-ordination among system operators, network operators, and DER owners

Regulatory Requirements	
Wholesale Market	VPP participation should be allowed in wholesale and ancillary service markets, Clear price signals to guide the VPP operations, Mandate implementation of smart grid infrastructure
Distribution	Local markets for DSOs to procure grid services, Rules to ensure consumer privacy

Stakeholder Roles and Responsibilities	
DER Aggregators (DERAs) / VPP	Provide grid services to DSOs, Information exchange with DSOs: capacity, location, DER type, etc.
DSOs	Procure market-based flexibility services from DERAs/VPP, Secured data sharing, Accurate DER and load forecasts

Thank You

www.nrel.gov

Contact: HarshaVardhana.Padullaparti@nrel.gov

NREL/PR-5D00-92831

This work was authored by NREL for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Policy. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL