NREL
Transforming ENERGY

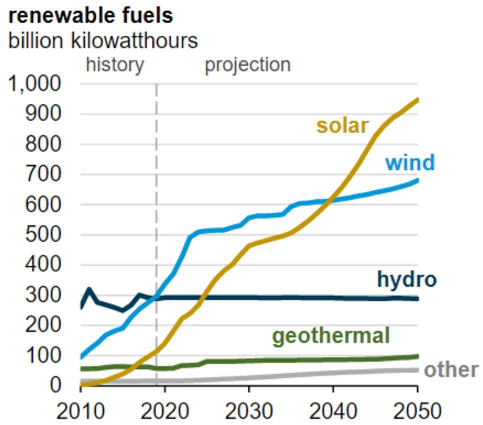
Distribution Grid Management in the Presence of Distributed Energy Resources

Harsha Padullaparti, Research Engineer, NREL
Illuminati Webinar, IEEE Student Branch NIT Warangal
December 16, 2022

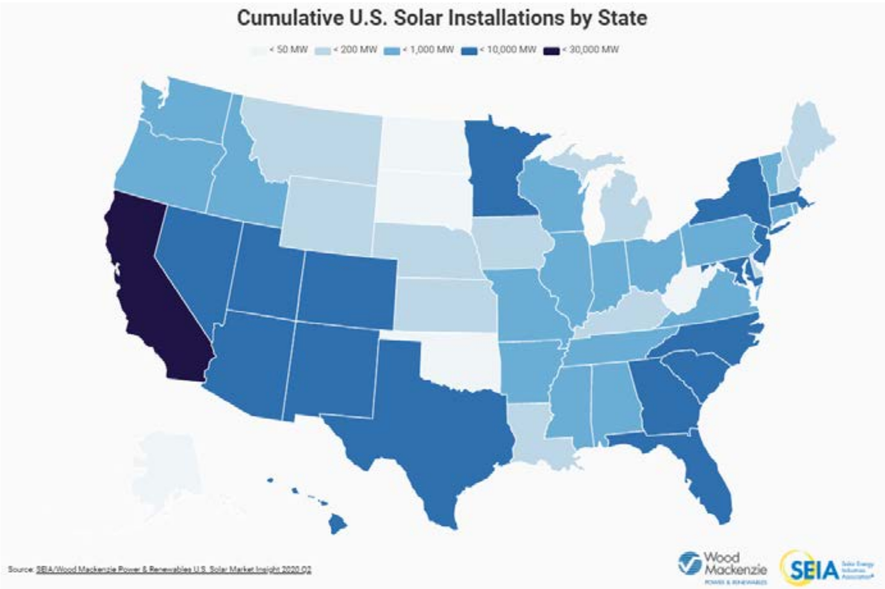
Photo by Dennis Schroeder, NREL 55200

Outline

- Background
- Advanced Distribution Management System (ADMS)
- Distributed Energy Resource Management System (DERMS)
- ADMS Test Bed at NREL
- Voltage Regulation using ADMS and DERMS
- Peak Load Management using ADMS and DERMS
- Phase Identification using AMI data



https://www.eia.gov/todayinenergy/detail.php?id=42655



Distributed Energy Resource levels are growing in the US and worldwide

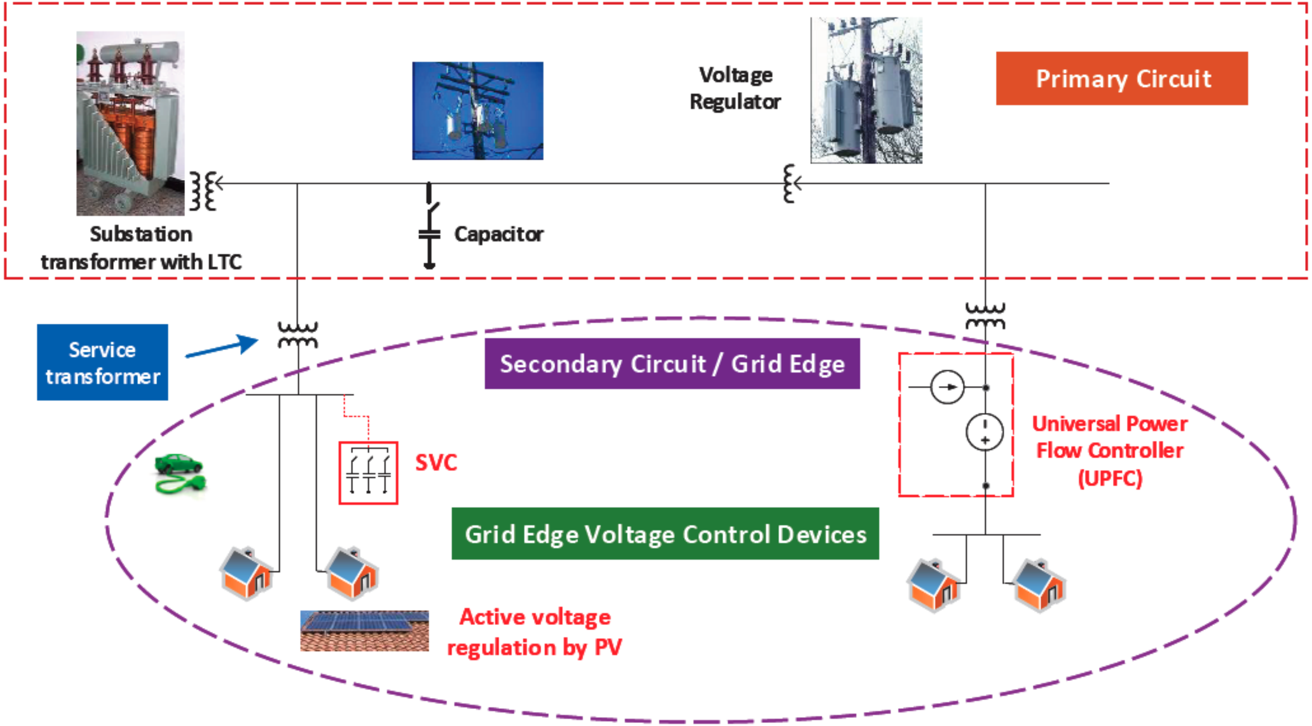
Distribution System

Medium Voltage (MV)

4 - 35 kV

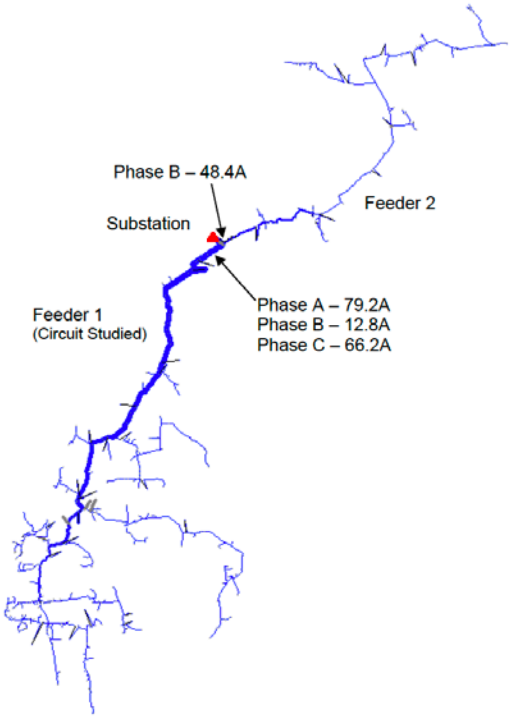
Low Voltage (LV)

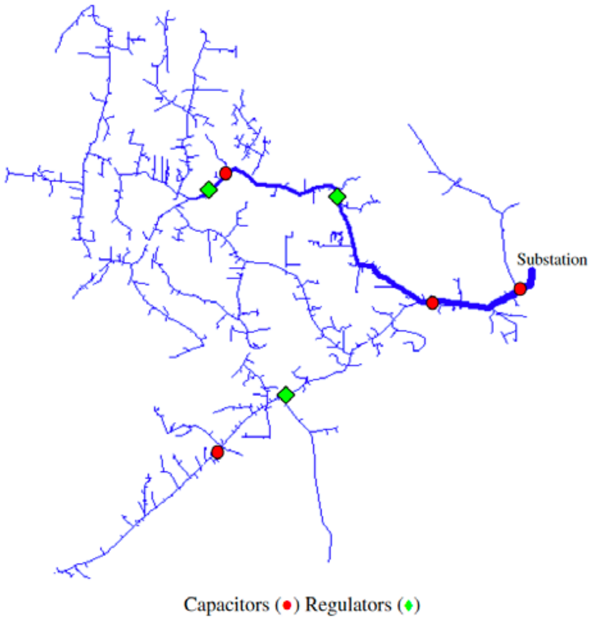
120/240 V



H. Padullaparti, "Edge-of-grid voltage control in distribution networks," Ph.D. dissertation, 2018. https://repositories.lib.utexas.edu/handle/2152/84953

Example Distribution Feeders





IEEE 8500-node test feeder

EPRI 1023518. "Green Circuits: Distribution Efficiency Case Studies." (2011).
https://www.epri.com/research/products/000000000001023518

Advanced Distribution Management System (ADMS)

- Legacy asset (LTC, VR, capacitor banks) operation using autonomous controllers
- Traditional DMS:
  - Enables distribution dispatchers to monitor and operate their system
  - Uses network model, SCADA, 3ph power flow
  - *Control and analysis functions:* Volt/VAR optimization (VVO), fault location isolation and service restoration (FLISR), load forecast, etc.

- ADMS platform integrates SCADA, GIS, DMS, OMS, EMS, etc.
- The integrated platform enables information exchange among these systems

H. V. Padullaparti, Q. Nguyen, and S. Santoso, "Advances in volt-var control approaches in utility distribution systems," 2016 IEEE Power and Energy Society General Meeting (PESGM), 2016, pp. 1-5.

Distributed Energy Resource Management System (DERMS)

- A DERMS is a software platform that manages behind-the-meter (BTM) DERs—such as rooftop photovoltaic solar panels, residential batteries, or a fleet of electric vehicles—to provide grid services
- Some DERMS can also manage front-of-meter (FTM) DERs
- May rely on ADMS to get network and power flow information
- DERMS technology is evolving

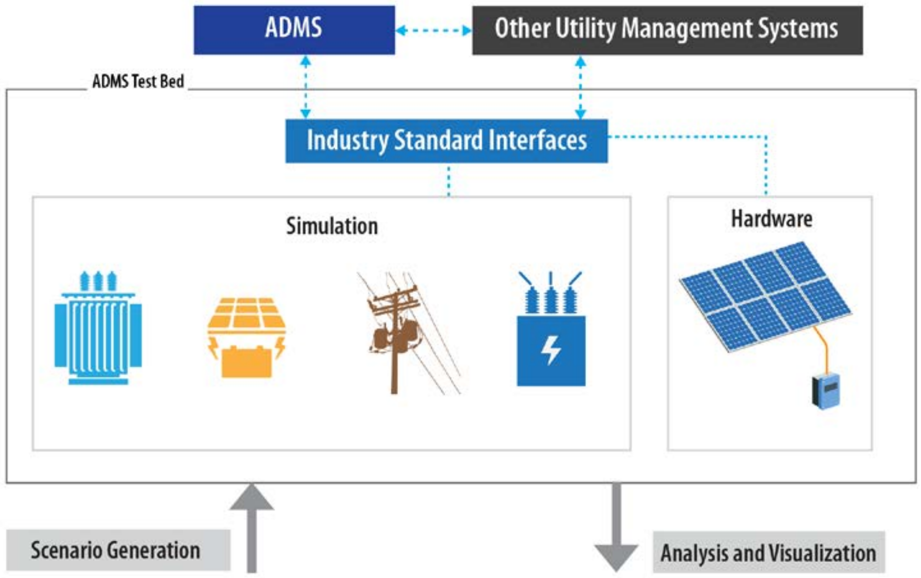
ADMS Test Bed at NREL

Goal: Accelerate industry adoption of ADMS to

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

Approach: Partner with utilities & 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



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

ADMS test bed capabilities:

- Multi-time scale co-simulation using HELICS (OpenDSS/OPAL-RT/RTDS)
- Hardware integration
- Communications interfaces
- Data collection & visualization

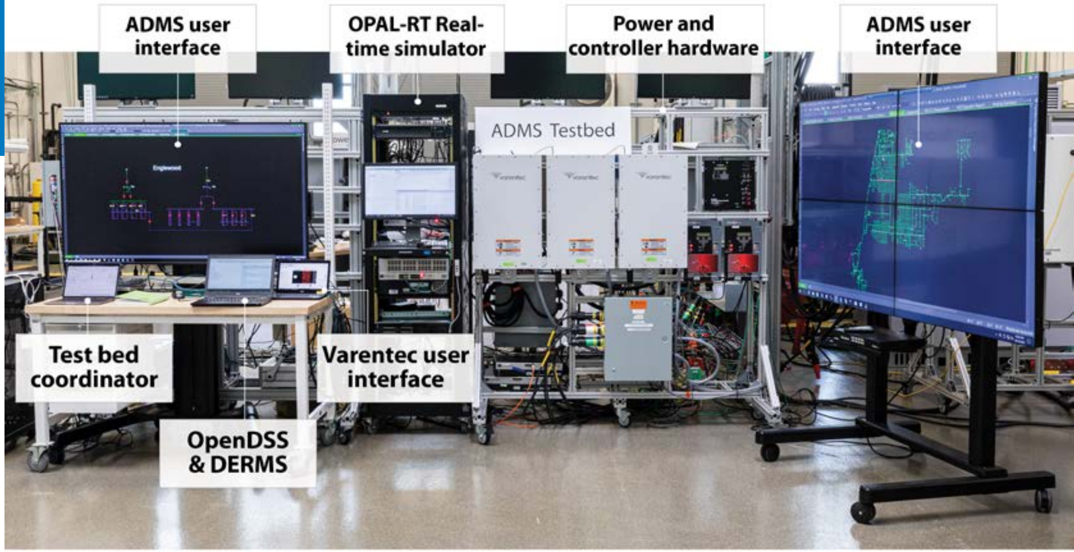
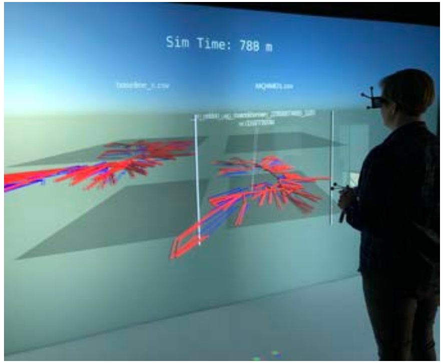


Photo by NREL

2D real-time visualization



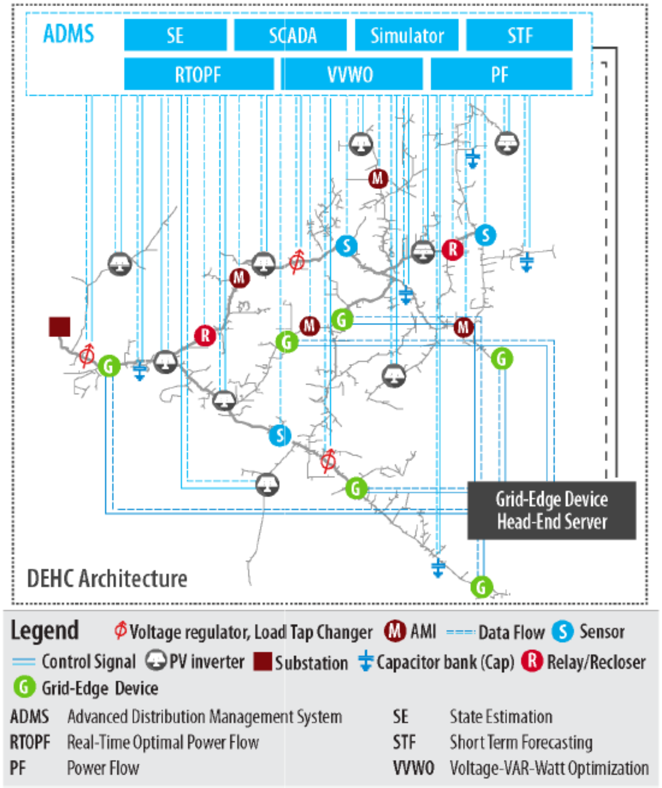
3D visualization

Photos by NREL

Voltage Regulation with ADMS and DERMS

Goal: Enable grid integration of very high PV generation by resolving voltage issues using coordinated ADMS and DERMS controls.

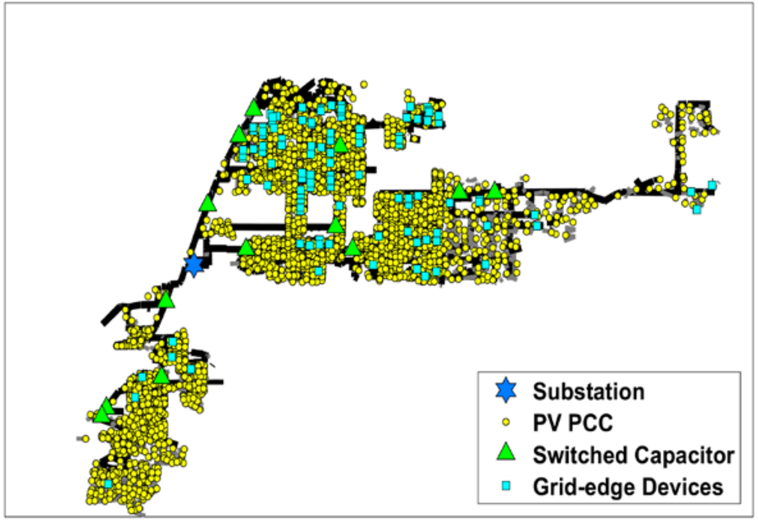
- Commercial ADMS
- Prototype DERMS based on real-time optimal power flow (RT-OPF)
- Real distribution network from a utility



H. Padullaparti, J. Wang, S. Veda, M. Baggu, and A. Golnas, "Evaluation of Data-Enhanced Hierarchical Control for Distribution Feeders With High PV Penetration," in IEEE Access, vol. 10, pp. 42860-42872, 2022.

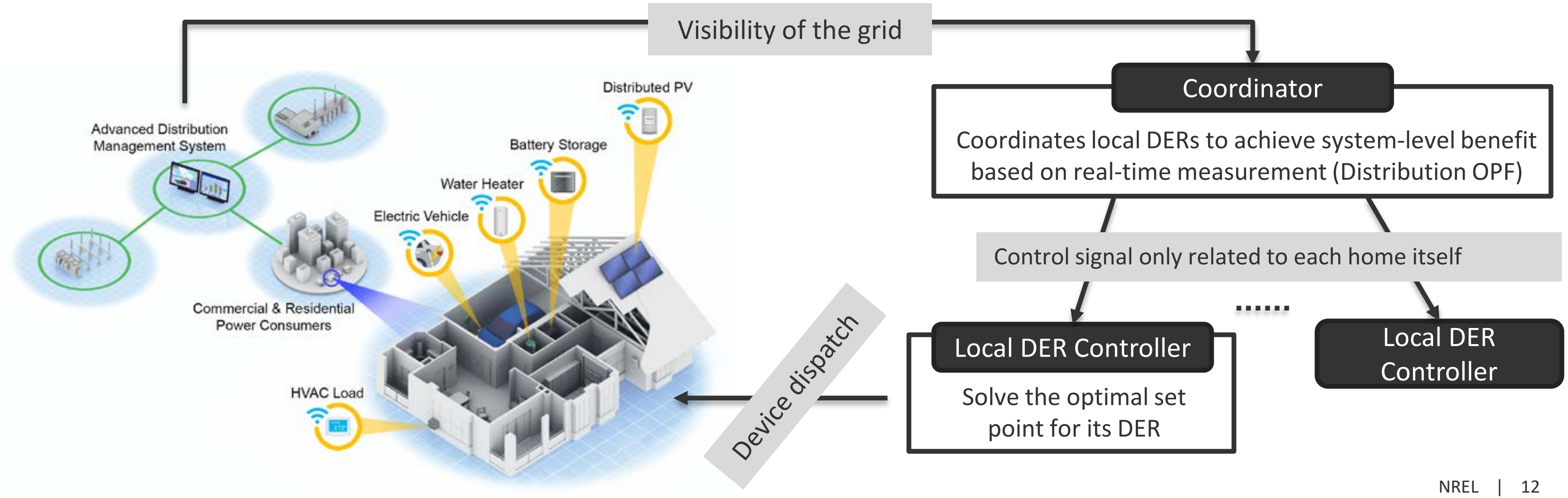
Distribution System Details

- 30 MVA, 110 kV/13.2 kV substation transformer
- 4 distribution feeders
- Serve nearly 6,000 customers
- More than 13,000 buses
- LTC, capacitor banks present
- Minimum load: ~12 MW
- Peak PV generation: ~24 MW; 200% relative to min. load
- 144 grid-edge devices



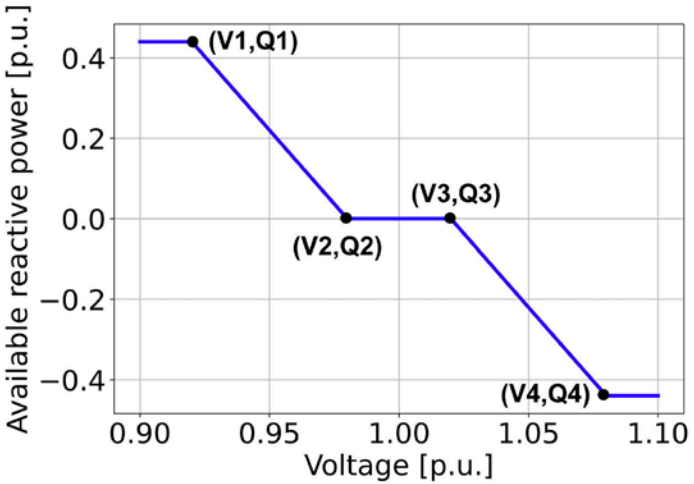
Prototype DERMS

- Originally developed at the National Renewable Energy Laboratory (NREL) under an Advanced Research Project Agency-Energy project
- Adapted for this project



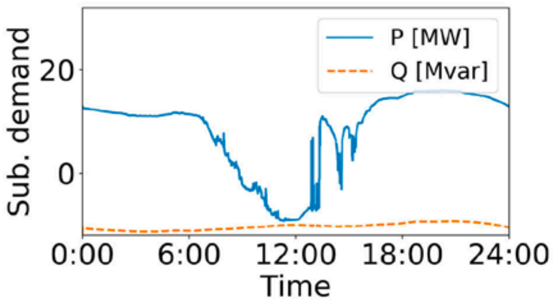
Simulation Scenarios

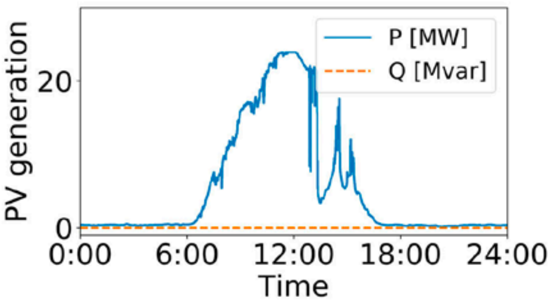
Scenario	Legacy devices	Grid-edge devices	Smart inverters
Baseline	Local control	Disabled	Unity power factor operation
S1	Controlled by the ADMS	Controlled by the GEMS/ADMS	Local control, follow Volt-VAR control curve
S2	Controlled by the ADMS	Controlled by the GEMS/ADMS	Follow RTOPF issued P, Q set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

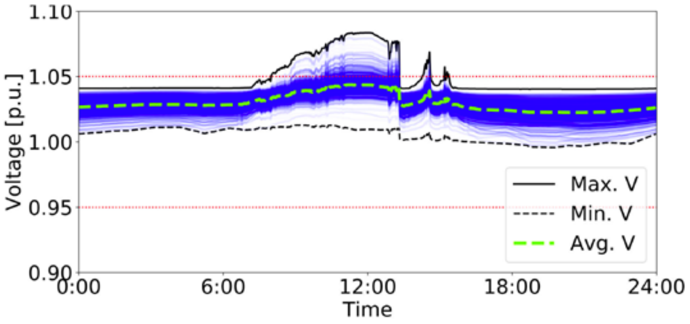


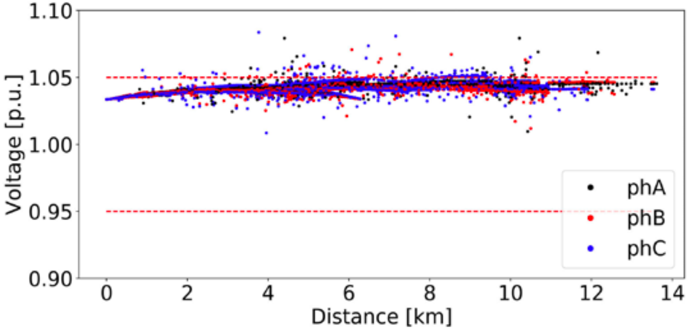
PV smart inverter Volt-VAR curve

Baseline Results



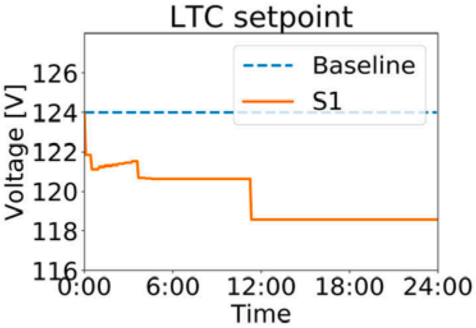


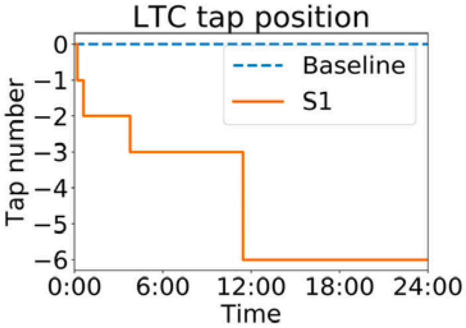


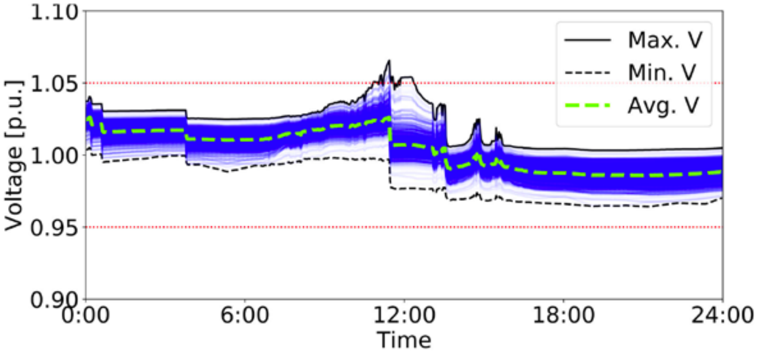


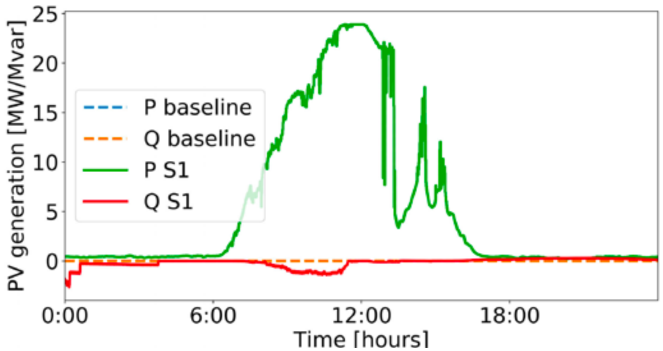
S1 Results

- PV smart inverters follow the volt-VAR curve, legacy devices controlled by ADMS, and grid-edge devices enabled



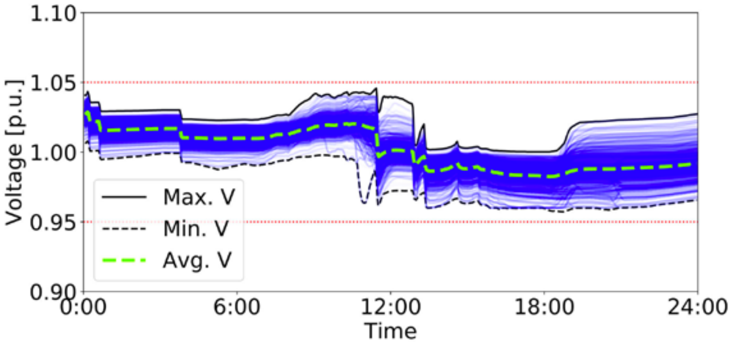


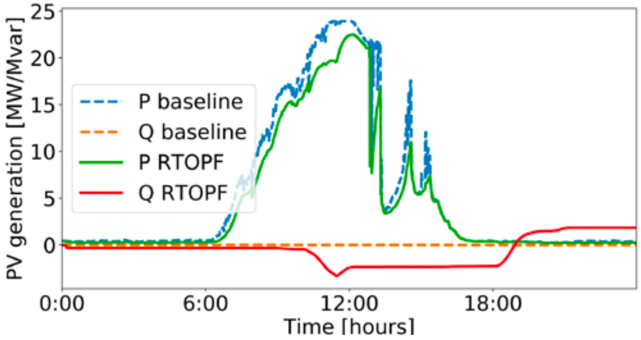




S2 Results

- PV smart inverters dispatched by RT-OPF DERMS, legacy devices controlled by ADMS, and grid-edge devices enabled



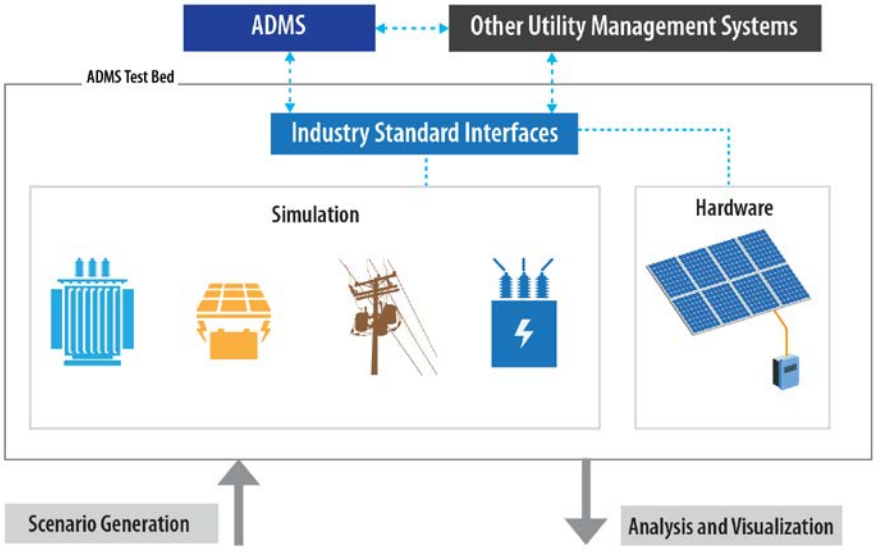


Parameter	**Baseline**	**S1**	**S2**
Energy delivered by PV [MWh]	132.1	132.1	111.0
PV energy curtailment [%]	0	0	16.0
Energy delivered by substation [MWh]	201.6	191.0	214.2
Voltage exceedances [node-hours]	1059.6	9.7	0.0

Peak Load Management with ADMS and DERMS

Goal: Evaluate the performance of peak load management coordinated across ADMS and DERMS.

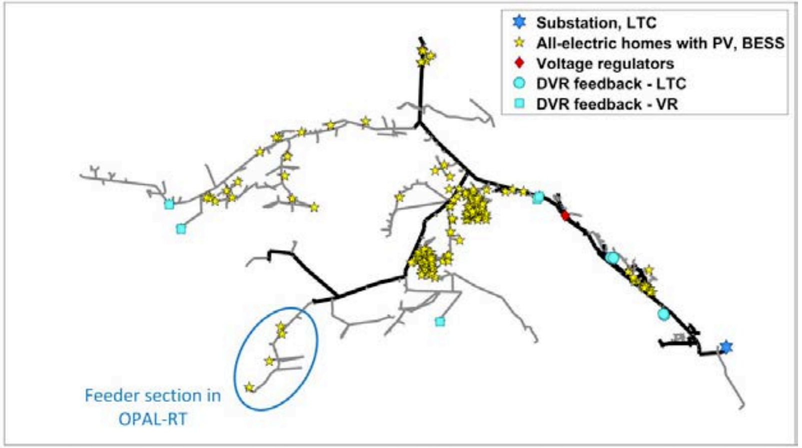
- Effectiveness of DERMS in complementing ADMS operations
- Communications interface between ADMS and DERMS



H. Padullaparti et al., "Peak Load Management in Distribution Systems Using Legacy Utility Equipment and Distributed Energy Resources," 2021 IEEE Green Technologies Conference (GreenTech), 2021, pp. 435-441.

Distribution Feeder Details

- 14.4 kV feeder
- LTC and voltage regulators present
- 163 all-electric homes in ~1100 loads
- Peak load: ~11 MW
- Rated residential PV: ~1.6 MW
- Residential batteries: ~ 1 MW, ~2.6 MWh

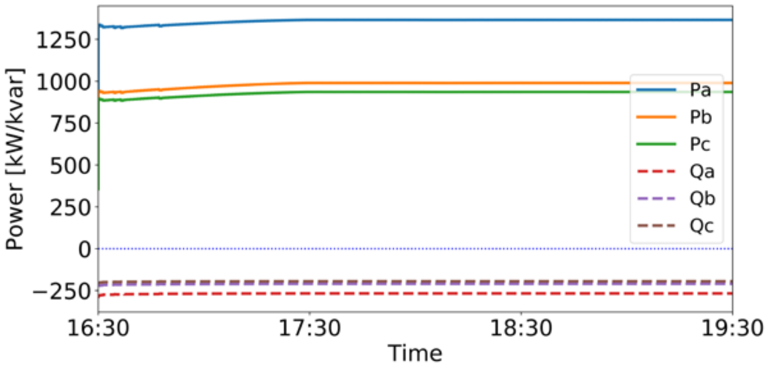


Simulation Scenarios

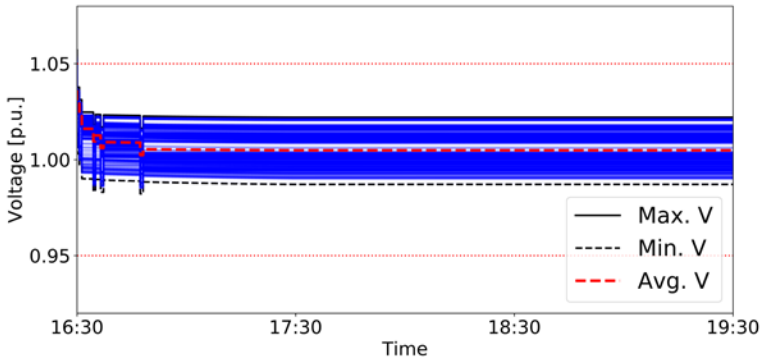
- DVR: Dynamic Voltage Regulation
- PLM: Peak Load Management

Scenario	**ADMS DVR**	**DERMS**
S0: Baseline	Disabled	PLM — disabled Voltage regulation — disabled
S1: DVR-Only	Enabled	PLM — disabled Voltage regulation — disabled
S2: DERM-Only	Disabled	PLM — enabled Voltage regulation — enabled
S3: DVR + DERMS	Enabled	PLM — enabled Voltage regulation — enabled

Baseline Results

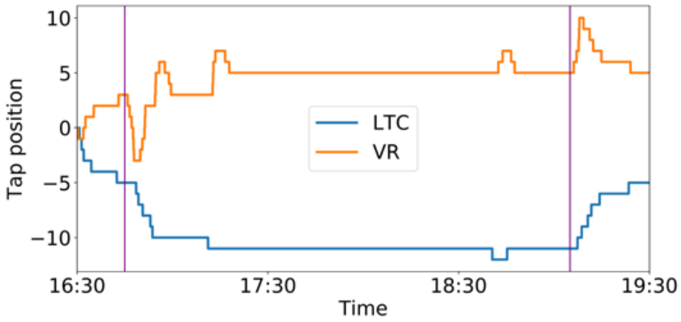


Feeder head powers

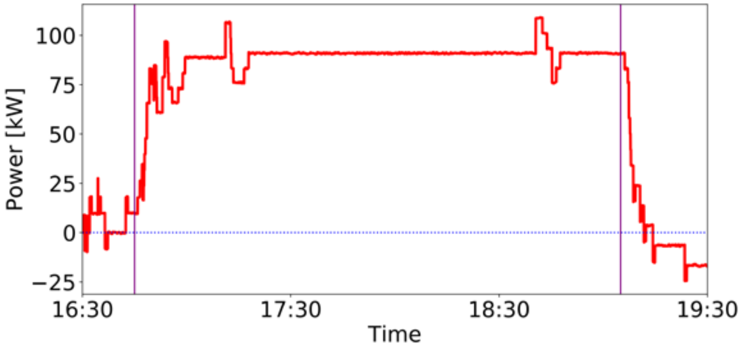


Bus voltages

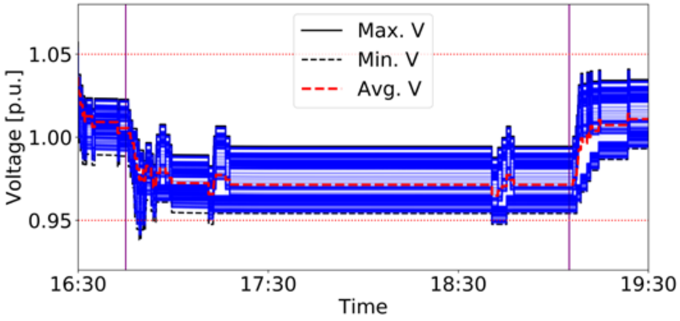
DVR-Only Results



Tap position status



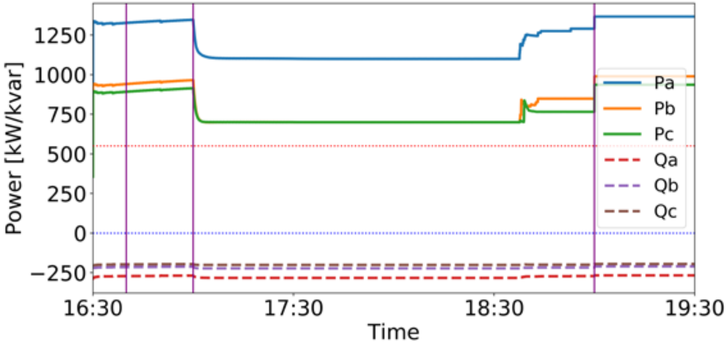
Substation demand deviation



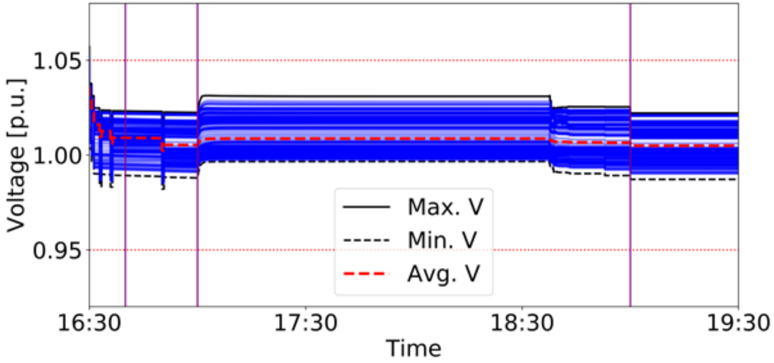
Bus voltages

Demand reduction is achieved through Conservation Voltage Reduction (CVR)

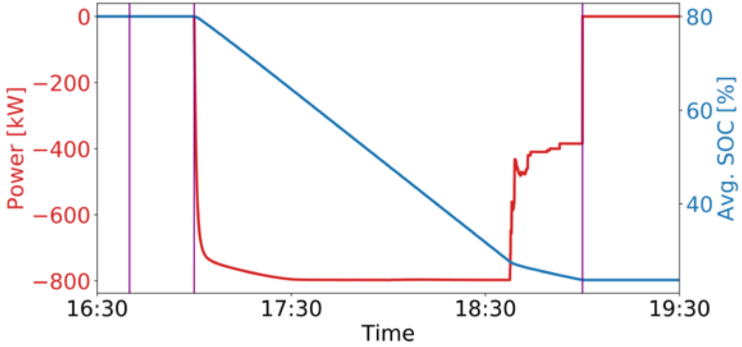
DERMS-Only Results



Feeder head powers



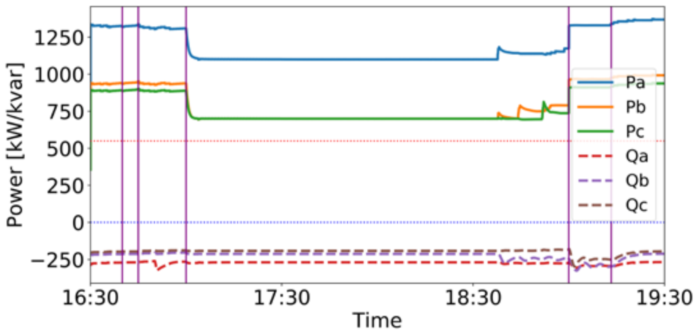
Bus voltages



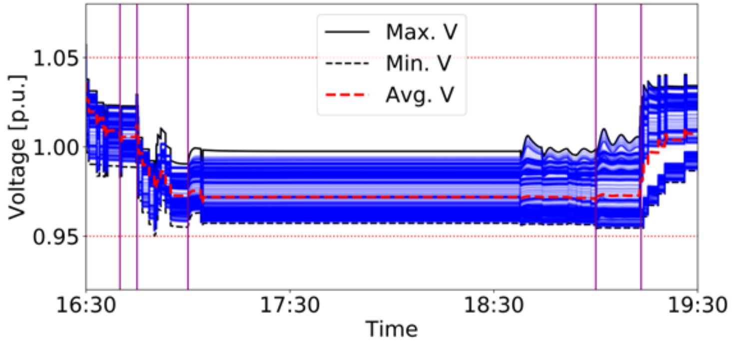
Total BESS power

Demand reduction is achieved through BESS power export

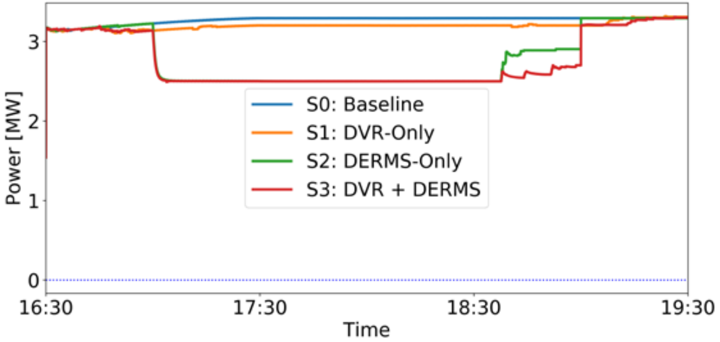
DVR + DERMS Results



Feeder head powers



Bus voltages



Substation demand comparison

Phase Identification using AMI data

Goal: Identify customer phase connectivity using advanced metering infrastructure (AMI) data

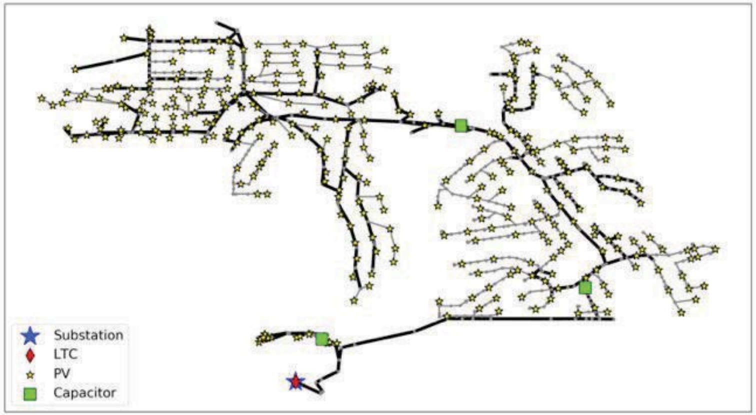
- Distribution grid management applications rely on network-models
- The phase connectivity database may become inaccurate over time
- Manual corrections using field checks are expensive and time-consuming
- Automated phase identification using AMI data is desired alternative
- Phase-to-neutral: A, B, C; Phase-to-phase: AB, BC, CA

H. Padullaparti, S. Veda, J. Wang, M. Symko-Davies, and T. Bialek, "Phase Identification in Real Distribution Networks with High PV Penetration Using Advanced Metering Infrastructure Data," 2022 IEEE Power & Energy Society General Meeting (PESGM), 2022, pp. 01-05.

Distribution Feeders

- 12 kV feeder, 10.3 MW peak load
- Serves more than 5,000 customers
- LTC and capacitor banks present
- Mostly overhead lines
- 70% PV generation (peak load)

- 12 kV feeder, 13.3 MW peak load
- LTC and capacitor banks present
- Mostly underground lines
- 24% PV generation (peak load)



Feeder 1

Feeder 2

Phase Identification Algorithm

- 5-minute average voltage AMI data collected in the field is used
- 30% training data

Algorithm 1 Phase identification using random forest classifier

1: Load AMI data set.

2: Perform data preprocessing: data cleaning and standardization.

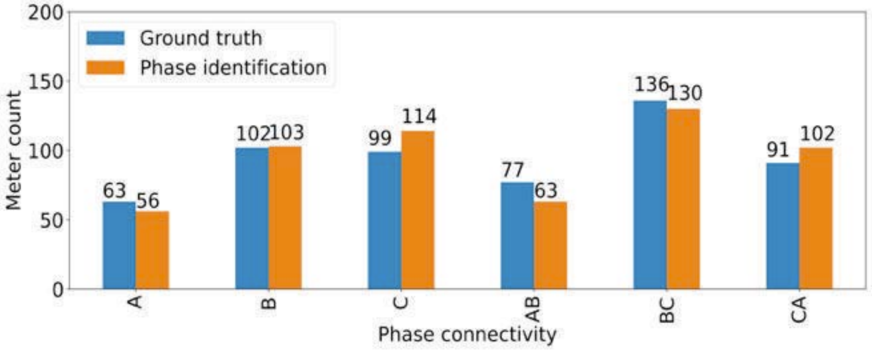
3: Load training data, including field-validated phase labels for the AMI meters in the training data.

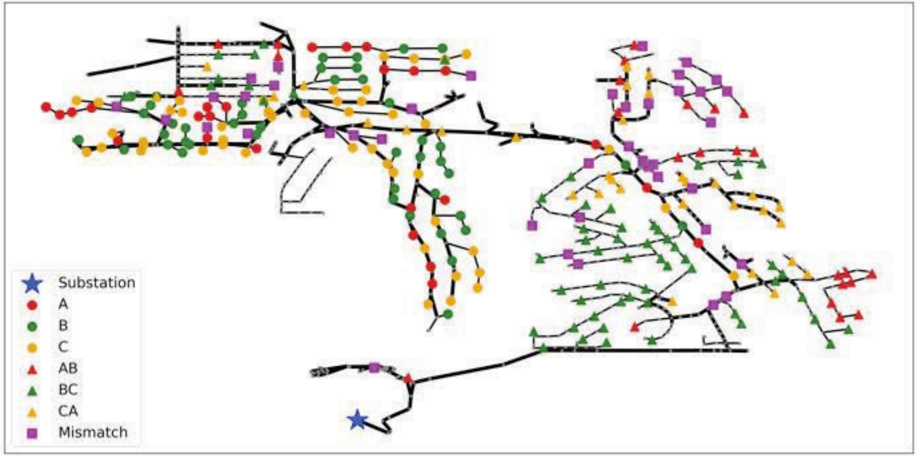
4: Construct a random forest classifier using the training data.

5: Input the voltage time-series testing data to the random forest classifier and obtain the corresponding phase connectivity.

6: Save the phase identification results for post-processing.

Feeder 1 Results

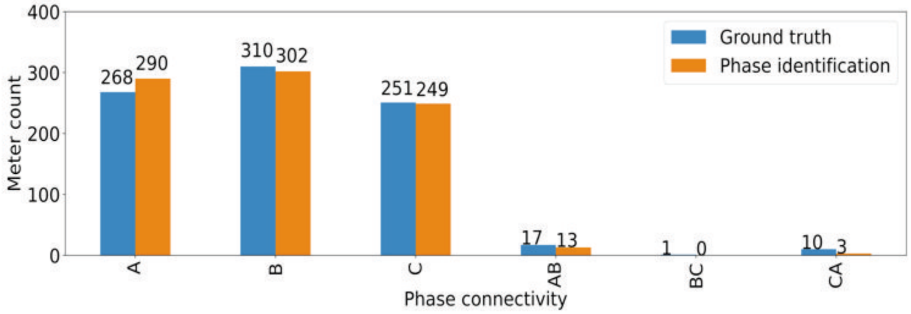


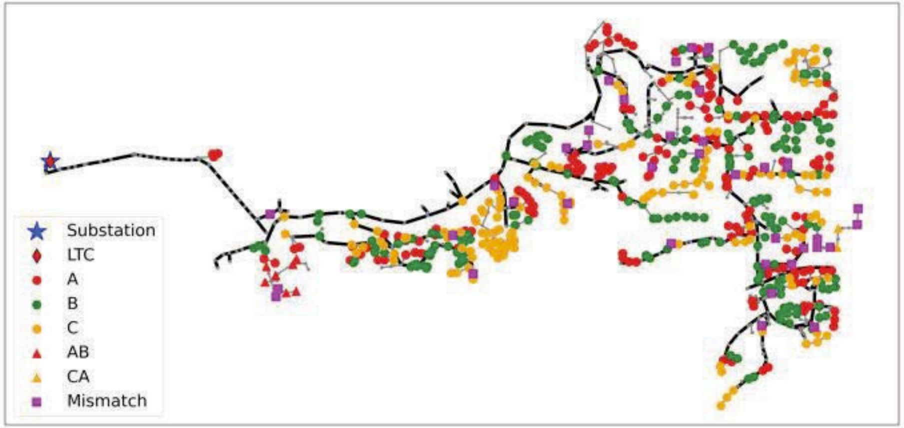


Data set	Phase label	Phase connectivity						Total
		A	B	C	AB	BC	CA	
Full	Ground truth	63	102	99	77	136	91	568
	Correct phase ID	55	98	98	56	126	81	514
Testing	Ground truth	45	72	70	54	96	64	401
	Correct phase ID	37	68	69	33	86	54	347
Training	Ground truth	18	30	29	23	40	27	167
	Correct phase ID	18	30	29	23	40	27	167

90% phase identification accuracy is achieved on the full dataset

Feeder 2 Results





Data set	Phase label	Phase connectivity						Total
		A	B	C	AB	BC	CA	
Full	Ground truth	268	310	251	17	1	10	857
	Correct phase ID	260	293	241	12	0	3	809
Testing	Ground truth	188	217	176	12	1	7	601
	Correct phase ID	180	200	166	7	0	0	553
Training	Ground truth	80	93	75	5	0	3	256
	Correct phase ID	80	93	75	5	0	3	256

94% phase identification accuracy is achieved on the full dataset

Thank You

www.nrel.gov

HarshaVardhana.Padullaparti@nrel.gov

NREL/PR-5D00-84827

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Electricity, Advanced Grid Research & Development. 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 Transforming ENERGY