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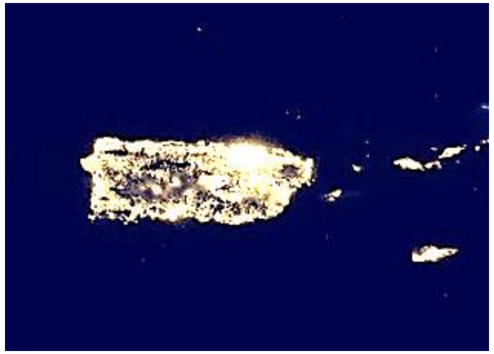


ProDROMOS: Managing Distribution Voltage using Photovoltaic Inverters

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U.S. DEPARTMENT OF ENERGY   NNSA

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ENERGISE ProDROMOS Project

Programmable Distribution Resource Open Management Optimization System (ProDROMOS)[1]

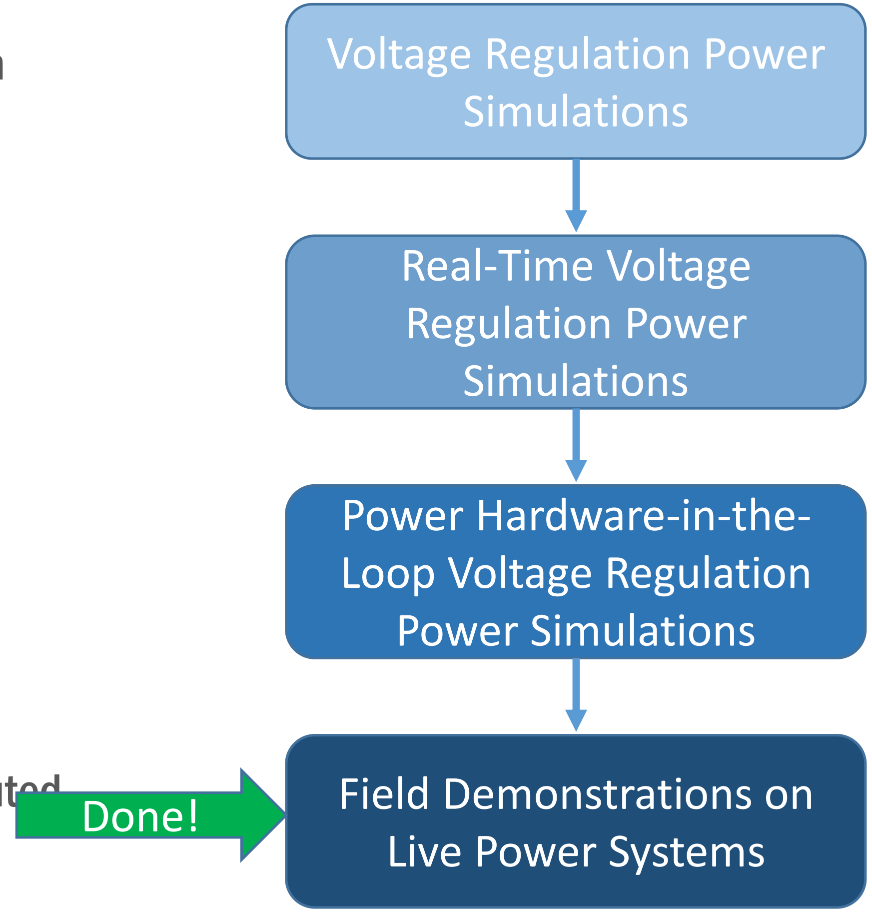
Create an Advanced Distribution Management System (ADMS) that:

- captures distribution circuit telemetry
- performs state estimation, and
- issues optimal DER setpoints based on PV production forecasts.

Implemented on a live power system using 684kW PV system

Compared three control strategies: autonomous, central optimization, distributed optimization

Adopted by Connected Energy (ADMS vendor)



[1]Prodromos is Greek for "forerunner" and the prodromoi were a light cavalry army unit in ancient Greece used for scouting missions.

OPAL-RT TECHNOLOGIES

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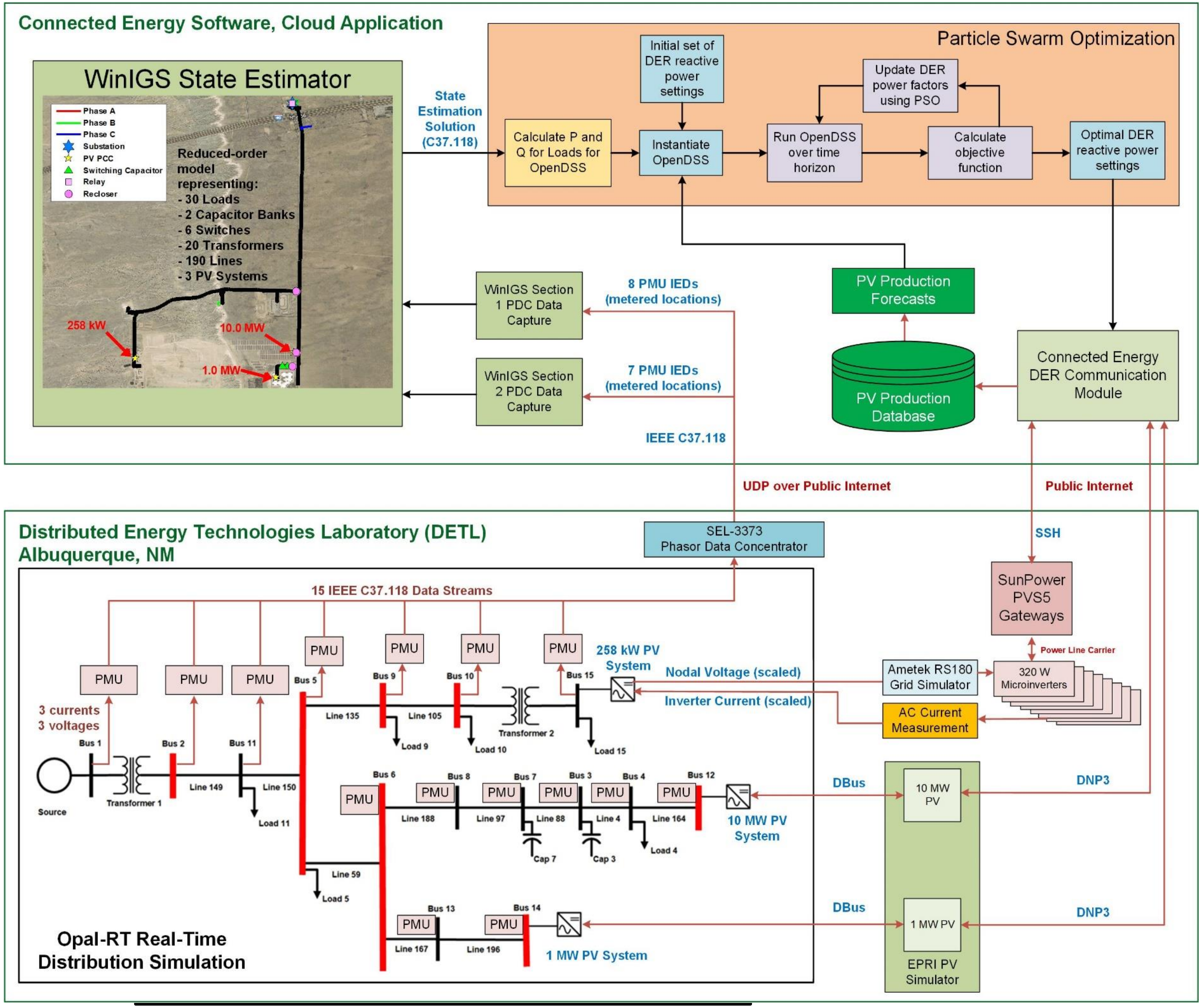
IMPLEMENTATION

Opal-RT Communication Interfaces

- PMU C37.118 to state estimator
- Opal DataBus Interface receives P/Q values for EPRI PV Simulators and transmits bus voltages and frequency

Information Flow

- The State Estimator ingests PMU data to produce current/voltage estimates for the distribution system
- State estimation data and PV generation forecasts populate an OpenDSS model.
- PSO wraps the OpenDSS model to calculate the optimal PF setpoints for each of the DER devices.
- DER PF settings are issued through proprietary SSH commands and IEEE 1815 (DNP3) commands



DIGITAL TWIN CONCEPT

Problem

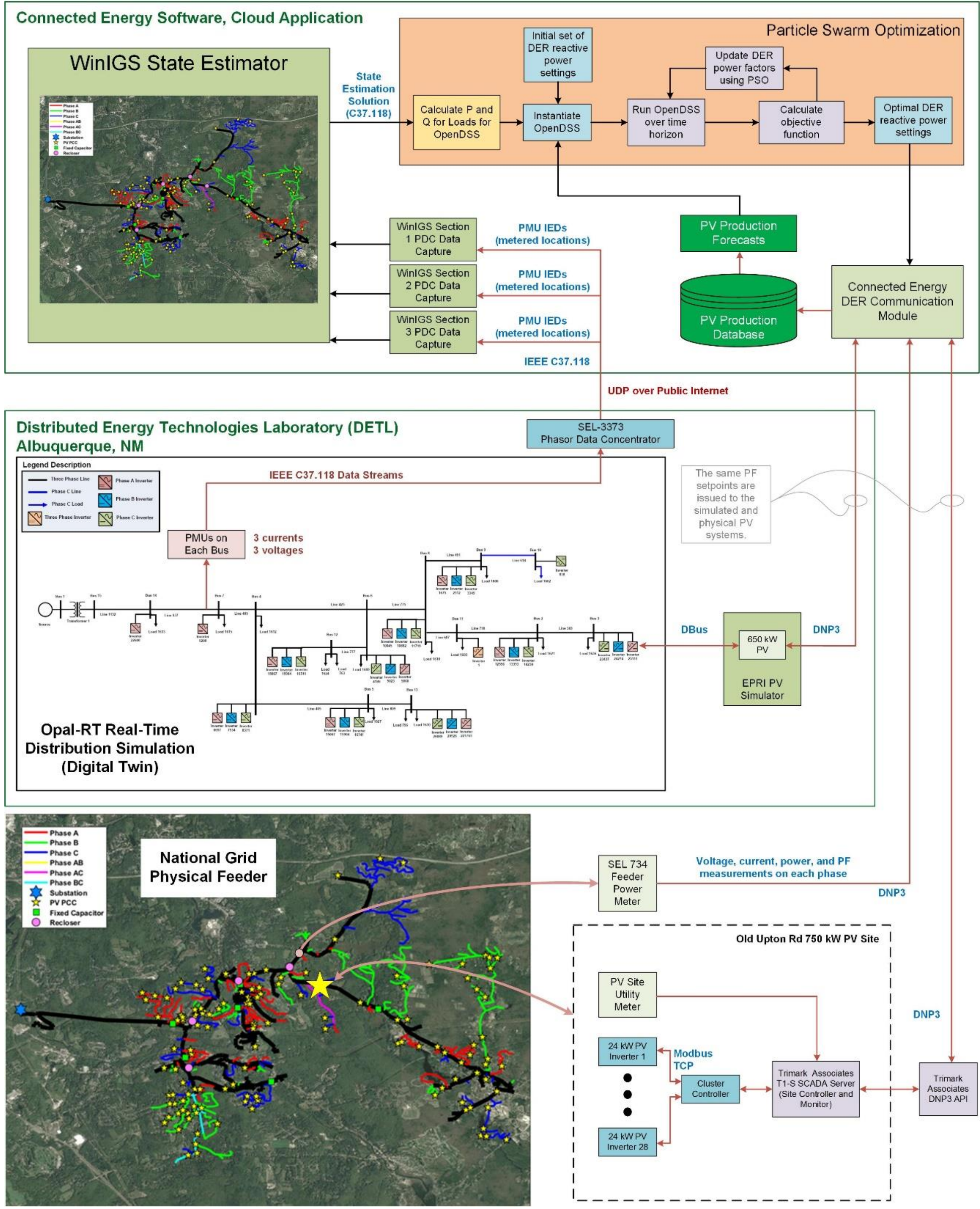
- Not enough Intelligent Electronic Devices (IEDs, i.e., PMUs, DERs, meters, etc.) to make state estimation observable for the field demonstration
- Short-term load forecasts or historical data is often used as “pseudo-measurements” to get a solution, but the team doesn’t have access to this data

Proposal

- Use a real-time digital twin of the feeder to estimate the system operations
  - If general behavior of digital twin is similar to the physical feeder, the “optimal” PF settings should support feeder voltages
- PV PF setpoints are sent to the physical and virtual PV system

Challenges

- This does not account for the current load (only pre-recorded versions)

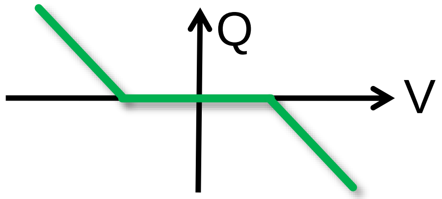


OPTIONS FOR VOLTAGE REGULATION USING GRID-SUPPORT FUNCTIONS

- **Distributed Autonomous Control**
  - Function: volt-var
  - Pros: Simple, requires little or no communications, DER locations not needed
  - Cons: does not reach global optimum

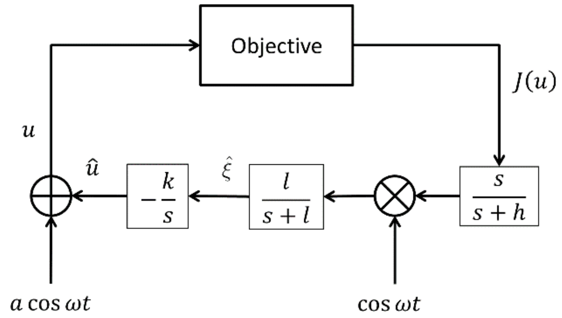
    Note: rather 'gentle' volt-var profile in this evaluation

Volt-Var Mode



- **Extremum Seeking Control (ESC)**
  - Function: new grid-support function
  - Pros: can achieve global optimum
  - Cons: requires fitness function broadcast (with new inverter function), careful selection of parameters

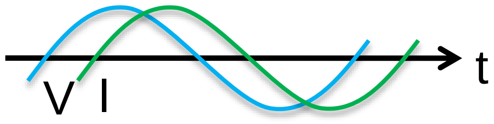
ESC



- **Particle Swarm Optimization (PSO)**
  - Function: power factor or reactive power commands
  - Pros: direct influence over DER equipment to achieve objective
  - Cons: requires telemetry, knowledge of DER locations, and state estimator/feeder model

    Note: Forecasting tool estimates PV power production

Optimal Power Factor



DISTRIBUTION CIRCUIT FEEDER MODEL

OpenDSS models were converted to reduced-order RT-Lab models

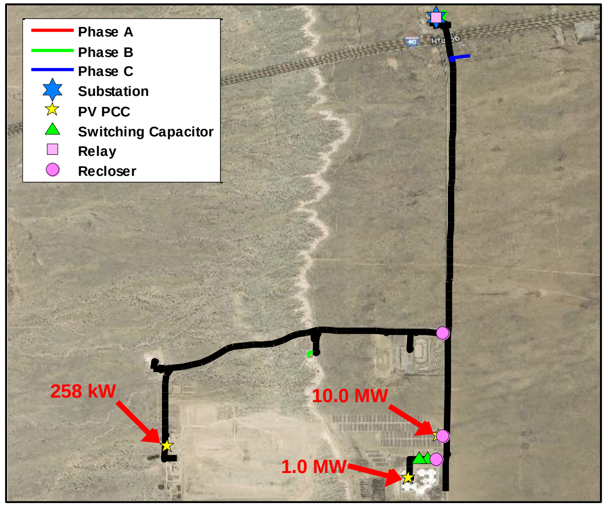
The PNM feeder has ~440% PV penetration because of large utility-scale PV systems.

Lines #	Transformers #	Loads #	Buses #	Voltage (V)	Load Power		PV Power (kVA)
					Active (kW)	Reactive (kVAR)	
12	2	14	15	7200/277	2568.63	1418.71	11258.00

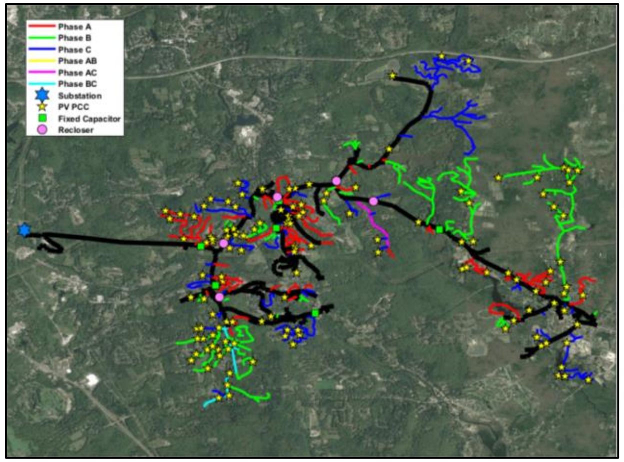
The NG feeder has 50% penetration chiefly as distributed PV.

Lines #	Transformers #	Loads #	Buses #	Voltage (V)	Load Power		PV Power (kVA)
					Active (kW)	Reactive (kVAR)	
13	3	43	15	8000	9494.76	318.10	5495.36

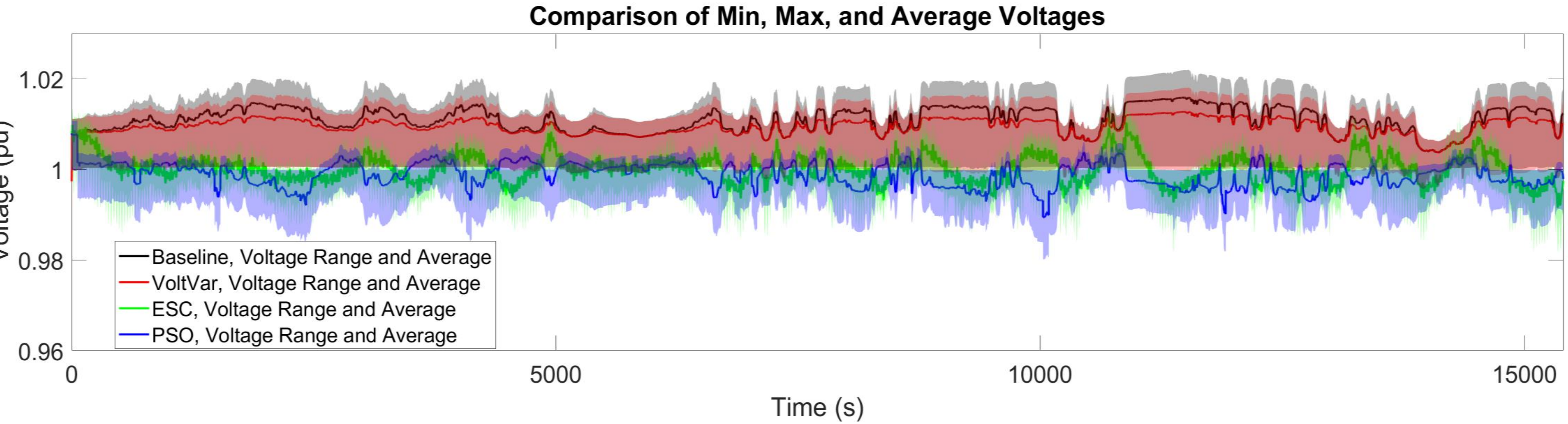
PNM Model



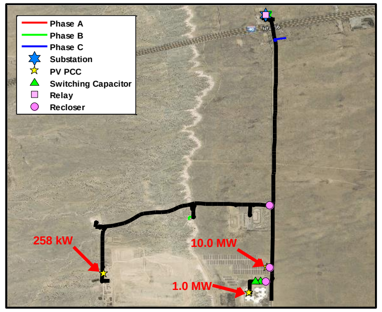
NG Model



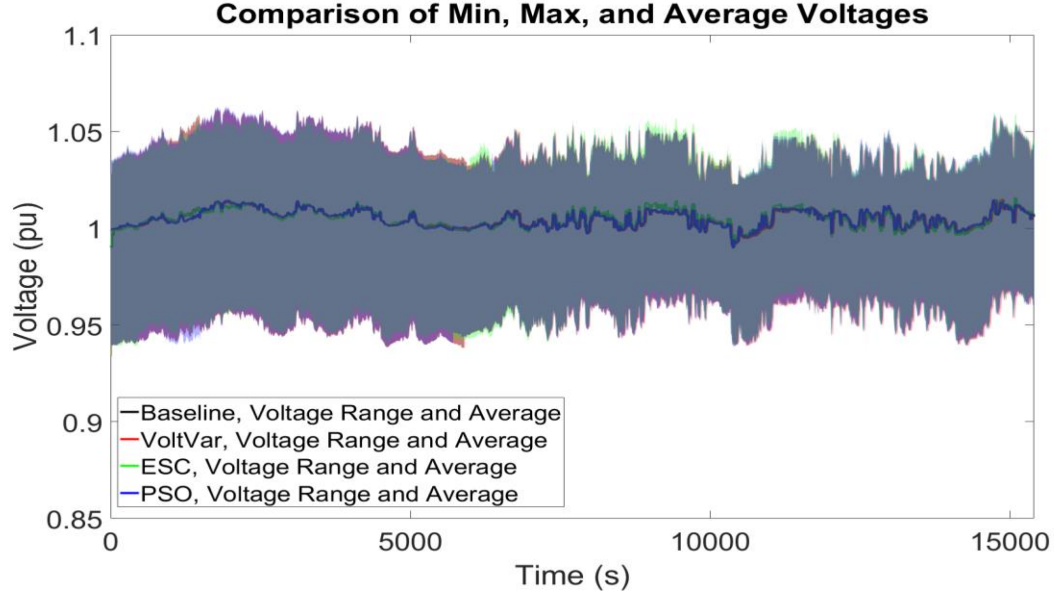
COMPARISON OF VOLTAGE REGULATION APPROACHES



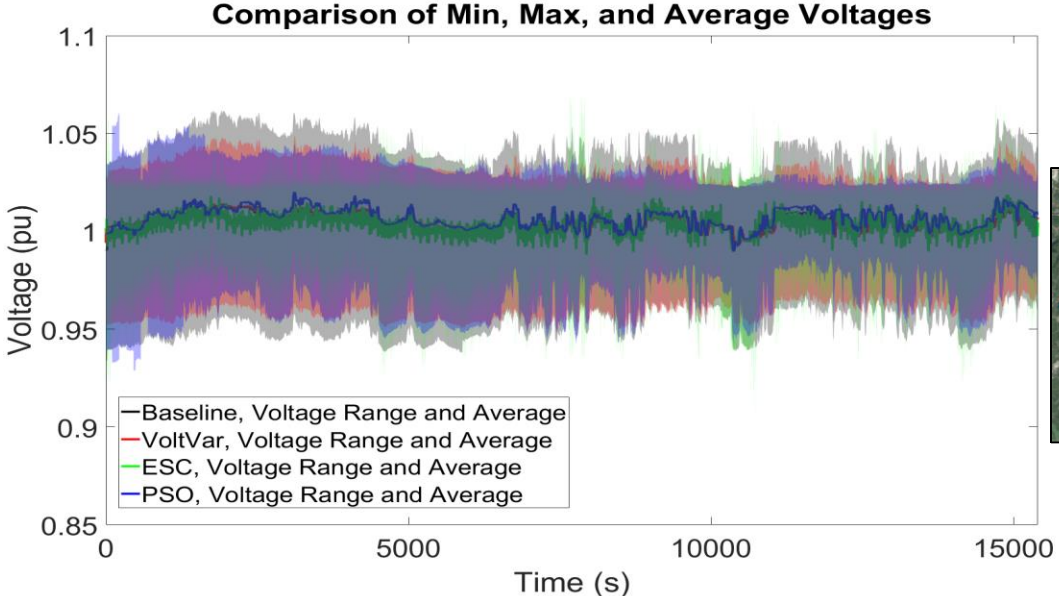
PNM Model



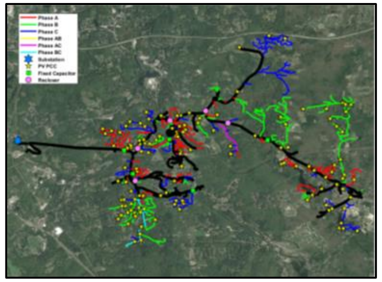
Single PV Control



All PV Control



NG Model



IMPACT OF EACH VOLTAGE REGULATION TECHNIQUE

A scoring approach is used to measure the effectiveness of each voltage regulation technique:

$$score = \frac{1}{T}\int_{t=0}^{t_{end}} \sum_{b=1}^{N} \left(|v_{bl} - v_{nom}| - |v_{reg} - v_{nom}| \right) dt$$

where,

v_{bl} : Baseline Voltage

v_{nom} : Target Voltage

v_{reg} : Voltage with control applied

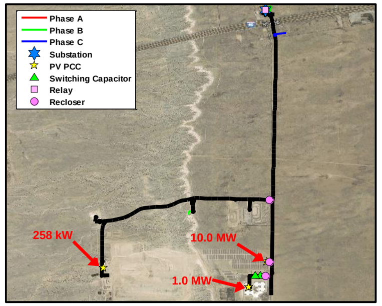
T: Time Period

b: bus

t: time

West Feeder Score					
	Phase A	Phase B	Phase C	Average	Improvement (%)
VV	0.024	0.024	0.024	0.071	12.9%
ESC	0.140	0.140	0.132	0.412	74.5%
PSO	0.139	0.139	0.130	0.408	73.7%
Best Score	0.186	0.188	0.179	0.553	

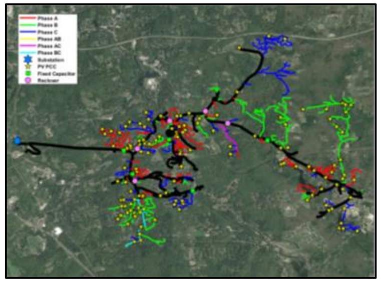
PNM Model



East Feeder Score Controlling a Single PV					
	Phase A	Phase B	Phase C	Average	Improvement (%)
VV	0.000	0.000	0.000	-0.001	0.0%
ESC	0.012	0.000	0.031	0.043	3.2%
PSO	-0.001	0.000	0.004	0.002	0.2%
Best Score	0.194	0.635	0.507	1.336	

East Feeder Score Controlling All PV					
	Phase A	Phase B	Phase C	Average	Improvement (%)
VV	-0.004	0.122	0.085	0.203	15.2%
ESC	-0.023	0.328	0.202	0.508	38.0%
PSO	-0.023	0.124	0.137	0.238	17.8%
Best Score	0.194	0.635	0.507	1.336	

NG Model



CONCLUSION

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- **Incremental development approach was effective** (simulation to real time to PHIL to field)
  - Communications between measurement equipment, ADMS controllers, and DER devices can be verified.
  - Build confidence in controls before field deployment.

- **Digital twin was necessary during development** to overcome sparse measurements for state estimation

- **Observations about control options**
  - **Volt-var** functionality provides some DER voltage regulation without communications.
  - In low communication environments, **extremum seeking control** is a viable means to control a fleet of DER devices to track toward optimal PF setpoints, but it is relatively slow and the system must be tolerant of probing signal ripple.
  - State estimation-fed, model-based **DER optimization** is a viable control strategy with sufficient telemetry.

- **Open question, and observations**:
  - How well could negative-sequence inverters regulate voltage on unbalanced feeders?
  - Available telemetry and communications will rarely supply what is assumed during ADMS development
  - Software interoperability continues to be challenging

Thank You!

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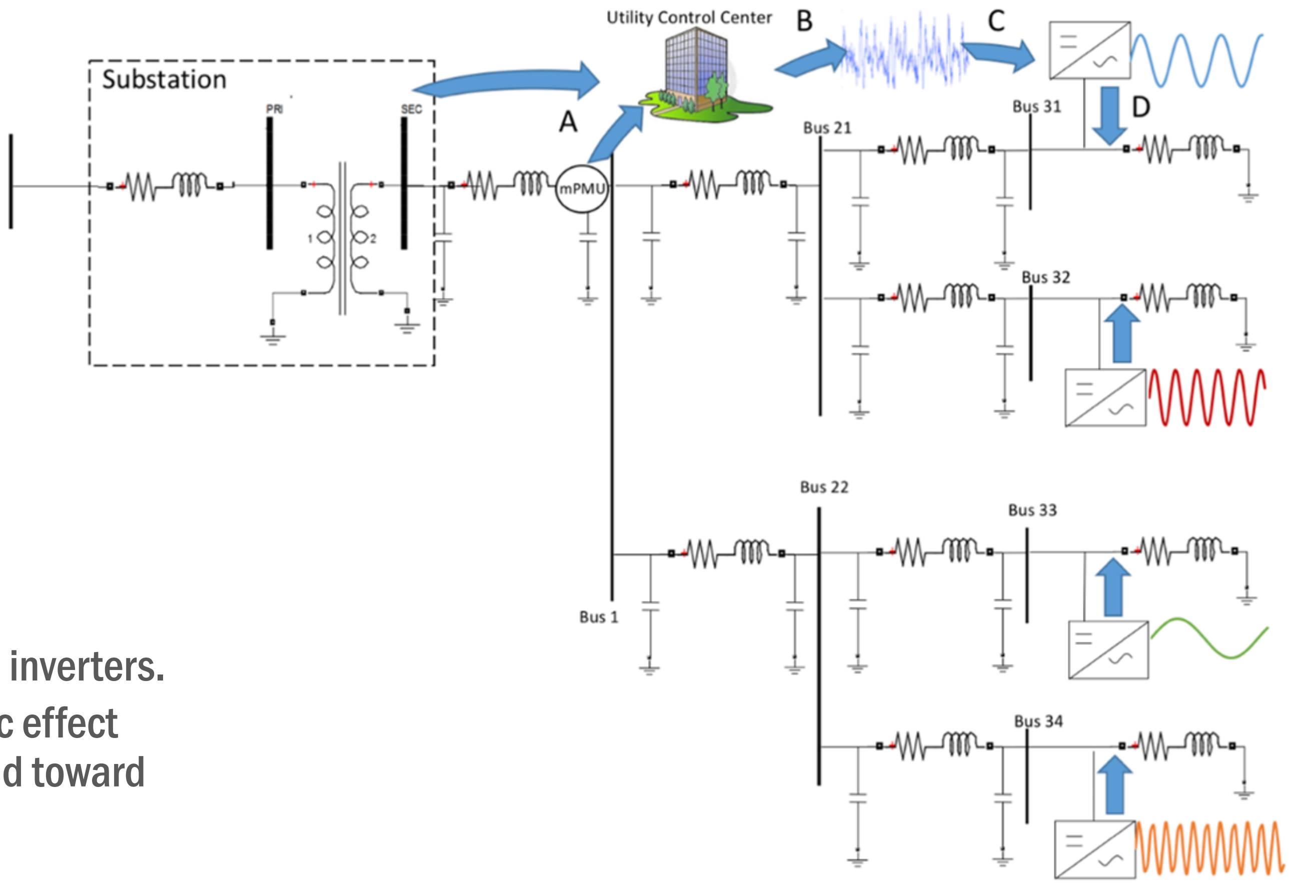
ESC



Extremum Seeking Control will be used as a comparison to the PF optimization technique

Steps in ESC:

A. Centralized control center collects data from the power system
B. Control center calculates the objective function, e.g., $J = 1/n*\Sigma[(V_i - V_n)/V_n]^2$
C. Control center broadcasts objective function to all inverters.
D. Individual inverters extract their frequency-specific effect on the objective function and adjust output to trend toward the global optimum.

- D. B. Arnold, M. Negrete-Pincetic, M. D. Sankur, D. M. Auslander and D. S. Callaway, "Model-Free Optimal Control of VAR Resources in Distribution Systems: An Extremum Seeking Approach," IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 3583-3593, Sept. 2016.
- J. Johnson, R. Darbali, J. Hernandez-Alvidrez, A. Summers, J. Quiroz, D. Arnold, J. Anandan, "Distribution Voltage Regulation using Extremum Seeking Control with Power Hardware-in-the-Loop," IEEE Journal of Photovoltaics, vol. 8, no. 6, pp. 1824-1832, 2018.
- J. Johnson, S. Gonzalez, and D.B. Arnold, "Experimental Distribution Circuit Voltage Regulation using DER Power Factor, Volt-Var, and Extremum Seeking Control Methods," IEEE PVSC, Washington, DC, 25-30 June, 2017.
- D. B. Arnold, M. D. Sankur, M. Negrete-Pincetic and D. Callaway, "Model-Free Optimal Coordination of Distributed Energy Resources for Provisioning Transmission-Level Services," in IEEE Transactions on Power Systems, vol. 33, no. 1, pp. 817-828, 2017.
- Code: https://github.com/sunspec/prodromos/blob/master/optimization/extemum_seeking_control.py

OPAL-RT TECHNOLOGIES

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PF OPTIMIZATION

- Optimization occurs every minute over a 15-min horizon
- OpenDSS simulation is instantiated with PV production forecast and current feeder status (which is assumed to persist)
  - State-estimation determines current feeder loads
  - Forecasting tool estimates PV power production
- Particle Swarm Optimization (PSO) is used to determine the optimal PF settings for the DER devices because of nonconvex fitness landscape

Objective Function:

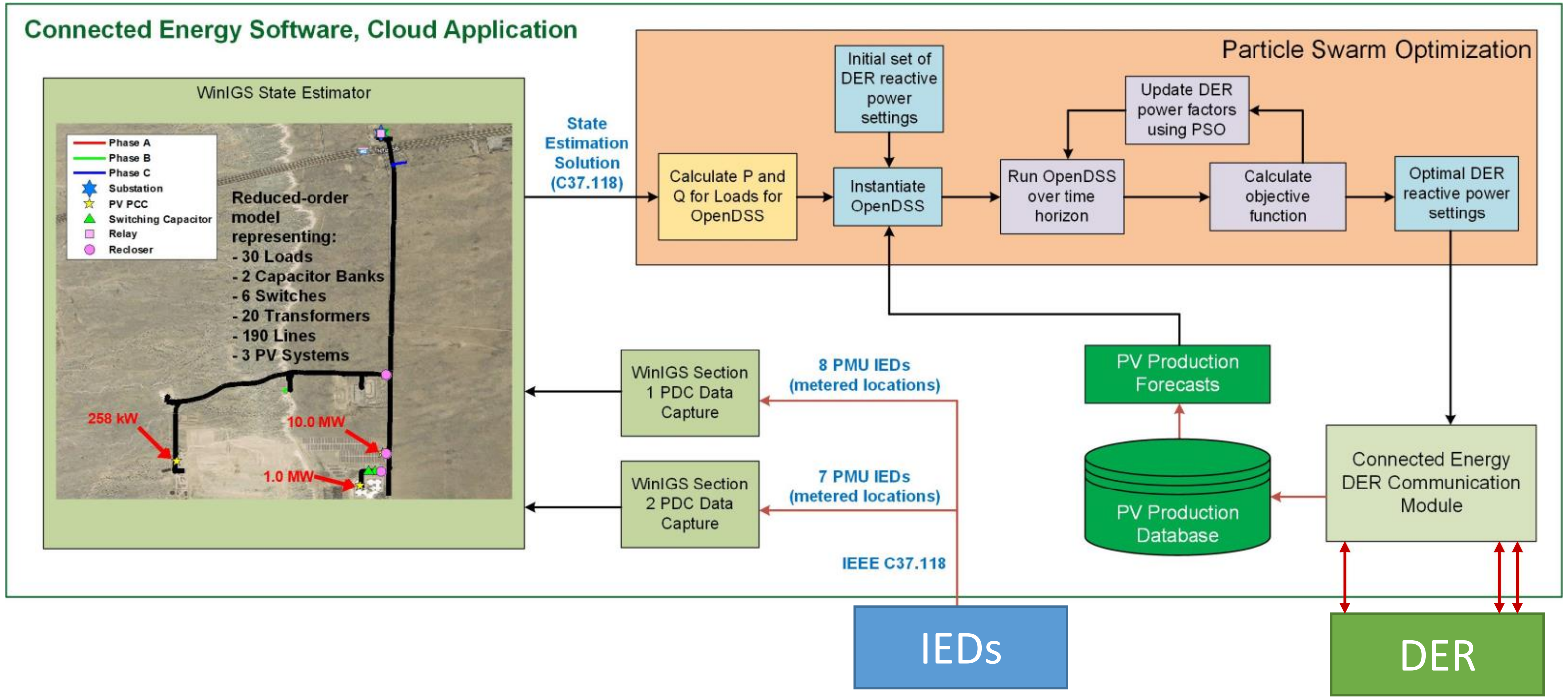
$$\min_{PF} w_0 \delta_{violation}(V) + w_1 \sigma(V - V_{base}) + w_2 C(PF)$$

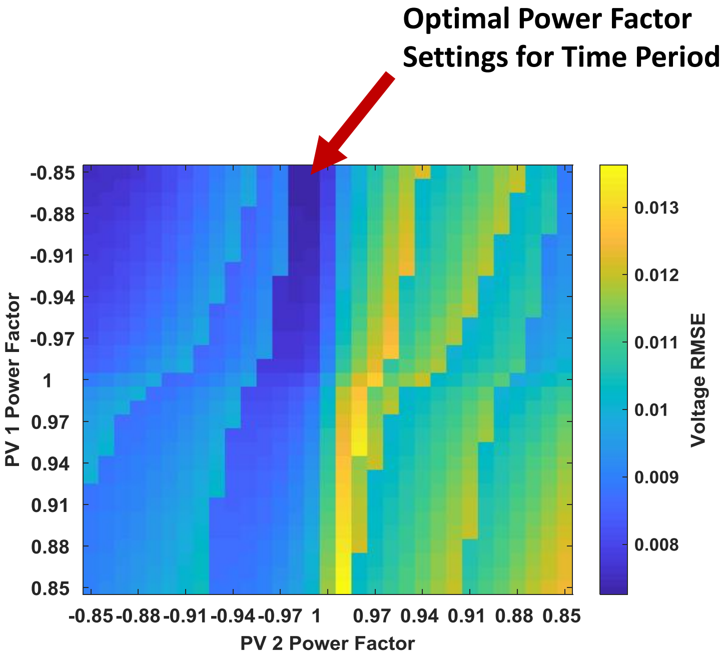
$$\delta_{violation}(V) = 1 \text{ if any } |V| > V_{\lim}$$

$$\sigma(V - V_{base}) \text{ is standard deviation of } V - V_{base}$$

$$C(PF) = \sum 1 - |PF|$$

Cost minimized when voltage = V_{base} and PF=1





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