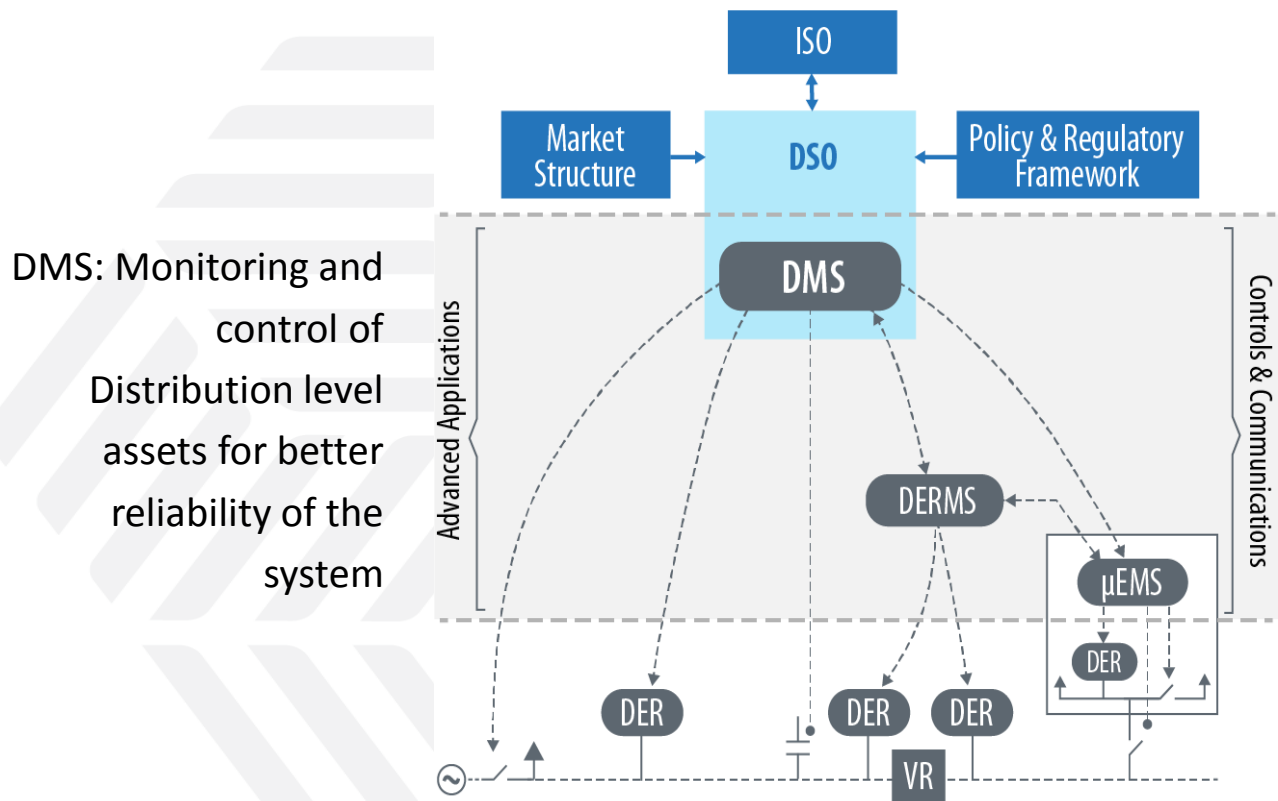# Advanced Distribution Management Systems and Distribution Automation

Murali Baggu (NREL) and Kevin Schneider (PNNL)

Distribution Systems and Planning Training
for New England Conference of Public Utility Commissioners, Sept. 27-29, 2017

Technological Advancements in Management Systems

DMS: Monitoring and control of Distribution level assets for better reliability of the system

DERMS: Monitoring dispatch and control of DERs

Microgrid Control and Management: Control, Schedule and Dispatch of assets with in the Microgrid for system resiliency

# Enterprise Systems Integration and Interoperability

- Seamless Integration among multiple systems

- Sharing common platform

- IT- OT convergence

- Cybersecurity

- Integration of different data systems to enhance decision making
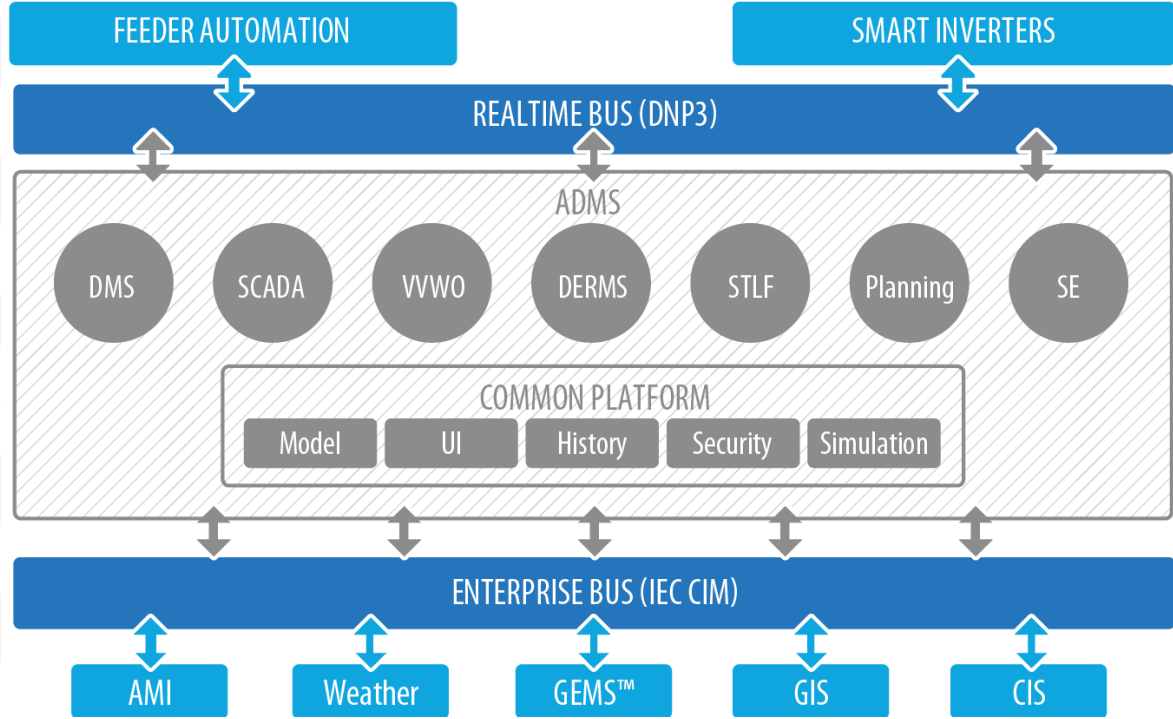
Short term Planning and Operations

Convergence of systems operations and short term planning

- Generate possible control scenarios for optimal system operation

- Spatial and temporal visualization of multiple scenarios and possible mitigation measures
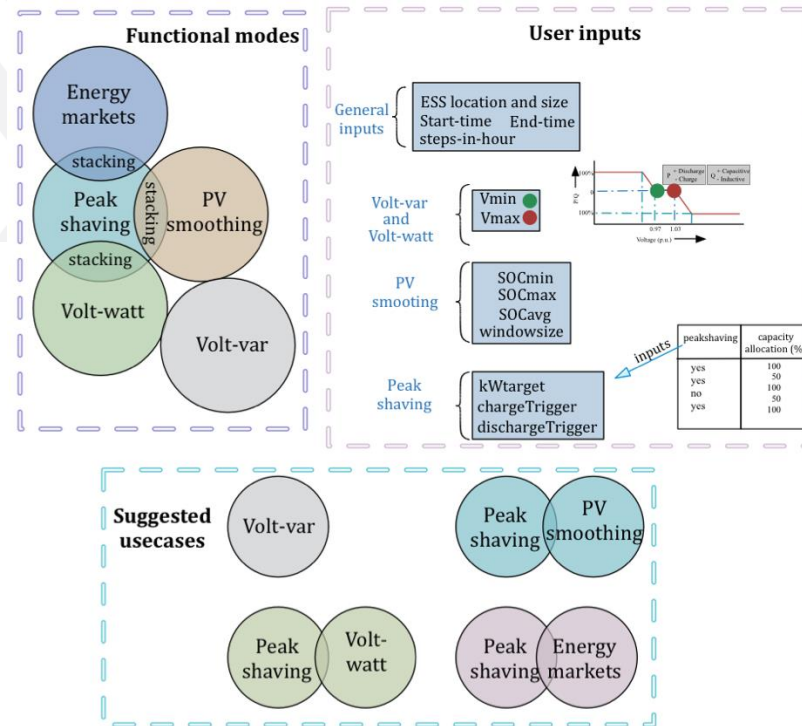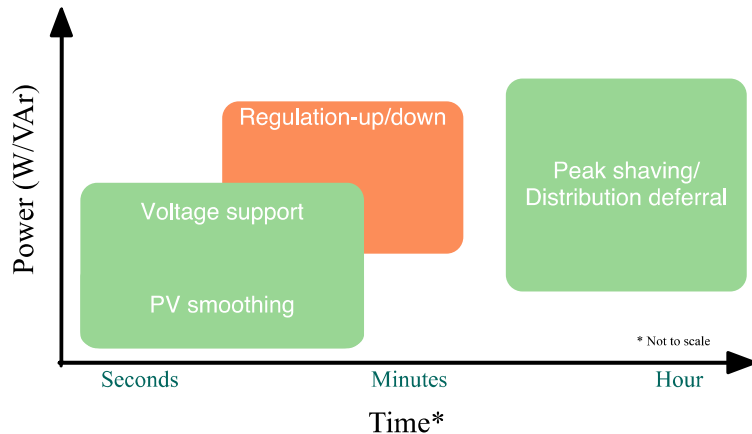
- Cost and Benefit Analysis
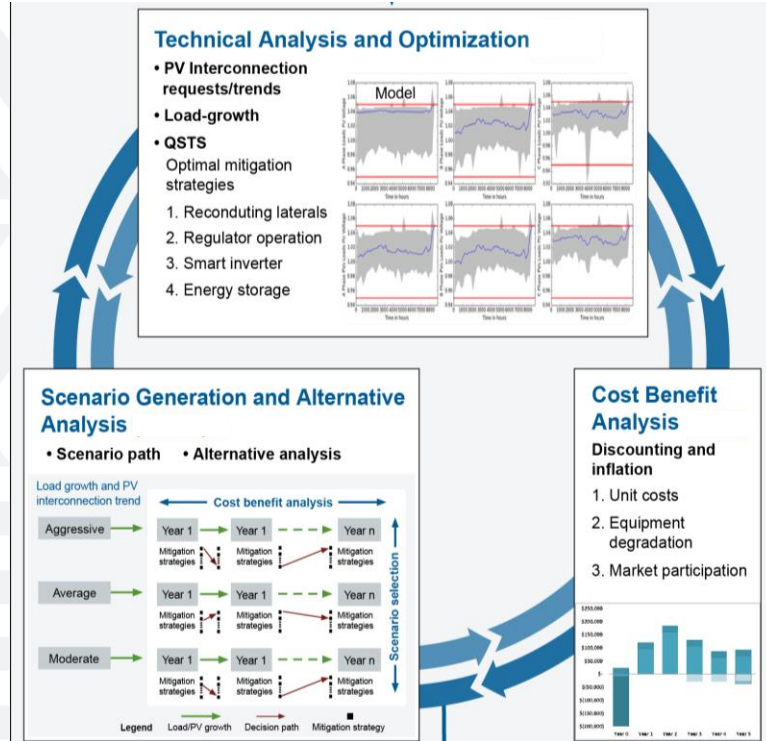
Distributed Energy Resource Management System

- DERMS provide situational awareness, control/dispatch and monitoring of DERs in the distribution system:
  - PV with and without smart inverters
 - Energy storage
  - Electric vehicles

Multi Service Dispatch of Energy Storage

- Understand the true value energy storage can generate when they are highly utilized by _**stacking**_ multiple grid services.

ADMS Testbed

Actual ADMS Deployment

- Tools to model large scale distribution systems for evaluating ADMS applications

- Integrate distribution system hardware for PHIL experimentation

- Develop advanced visualization capability

What Makes Grid Smart?

- New intelligent devices

- New data analytics and predictive analytics techniques

- Foundational optimization and control theory methods

- New Business Models (eg., "PaaS" (Platform as a Service) or "SaaS" (Software as a Service))

- Tools for modeling, simulation and visualization
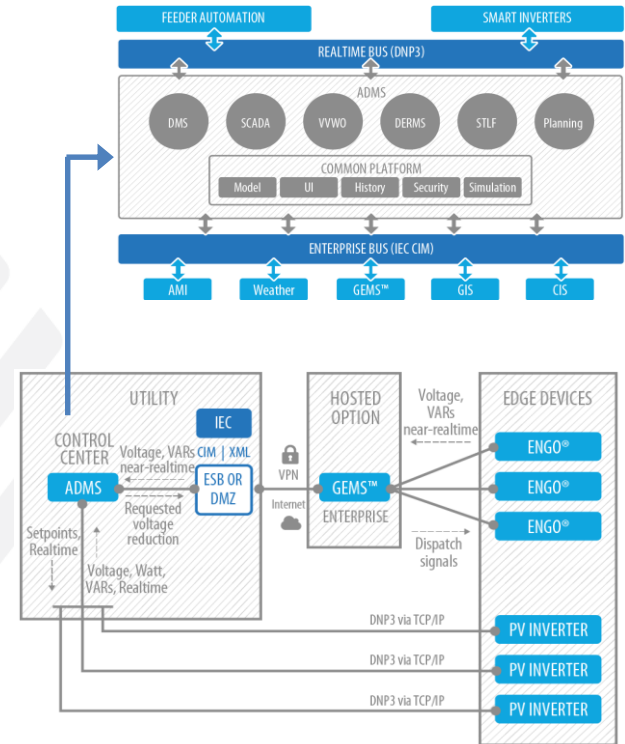
Distribution Management System

A Decision Support System to assist the control room and field operating personnel with the monitoring and control of the electric distribution system in an optimal manner while improving safety and asset protection

1) Network Connectivity Analysis (NCA)
2) State Estimation(SE)
3) Load Flow Applications (LFA)
4) Volt/ VAR Optimization (VVO)
5) Load Shed Application(LSA)
6) Fault Location, Isolation & System Restoration (FLISR)
7) Load Balancing via Feeder Reconfiguration (LBFR)
8) Distribution Load Forecasting
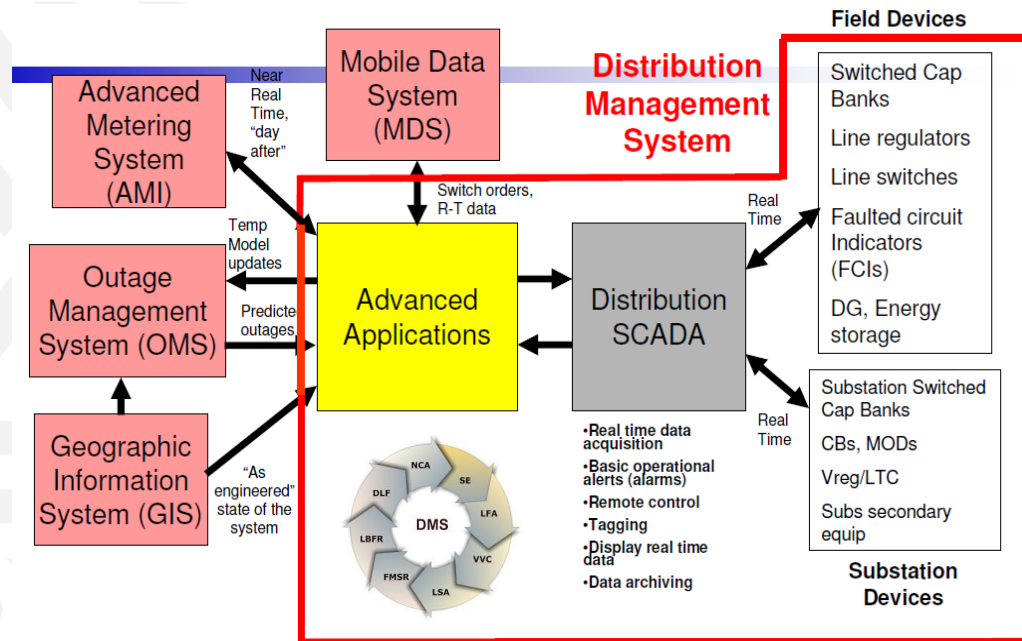
*Slide Source: http://www.smartgridnews.com/artman/uploads/1/Distribution_Management_Systems_-_Robert_Uluski.pdf and http://distributionmanagementsystem.blogspot.com/

Distribution Grid Modernization – Advanced Distribution Management Systems Applications

Volt-VAR Optimization

Volt-VAR Optimization (VVO)

► In contrast to the traditional operational methods, Volt-VAR Optimization controls multiple devices to achieve a global optimum.

► Volt-VAR Optimization, and the associated global optimum(s), exists in many forms.

► The general principle is to control the voltage and reactive power on a distribution feeder so that load can be managed.

► One example of VVO:

  ☐ Voltage optimization involves "flattening" the voltage profile and lowering.

  ☐ VAR optimization involves controlling the flow of reactive power, which has an impact on voltage.

Volt-VAR Optimization

► Voltage Reduction

  ☐ Voltage is reduced to the low end of ANSI C84.1, customer voltage never go below 114V.

  ☐ Rule of thumb: for every 1% reduction in voltage, there is a 0.7% reduction in energy consumption.

  ☐ The majority of energy savings, >90%, are behind the customer meter.

► VAR Optimization

  ☐ Capacitors are switched to reduce the reactive power flow on the feeder.

  ☐ This reduces the series losses of the line, increasing efficiency.
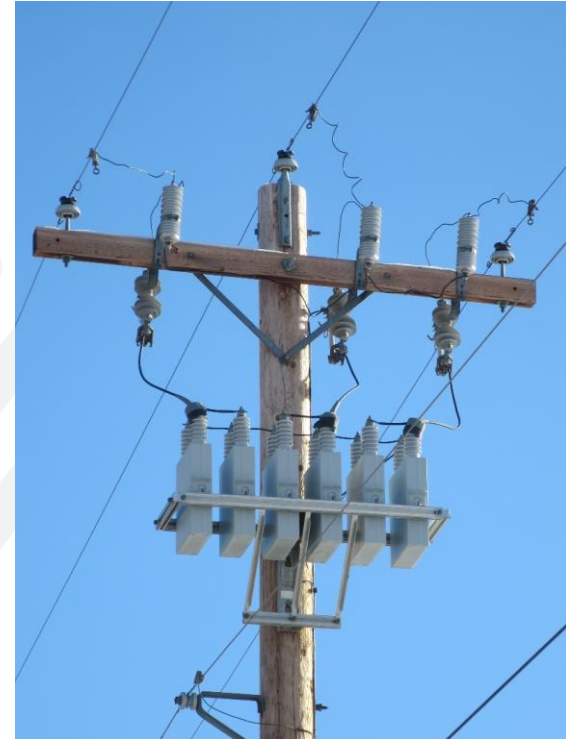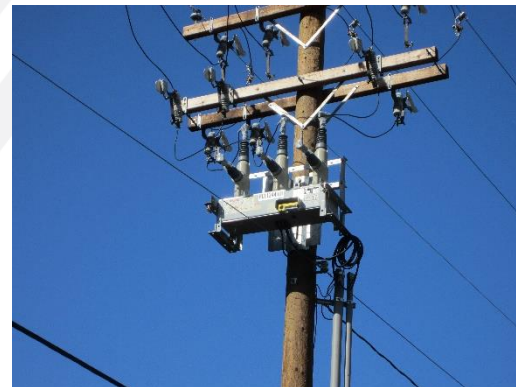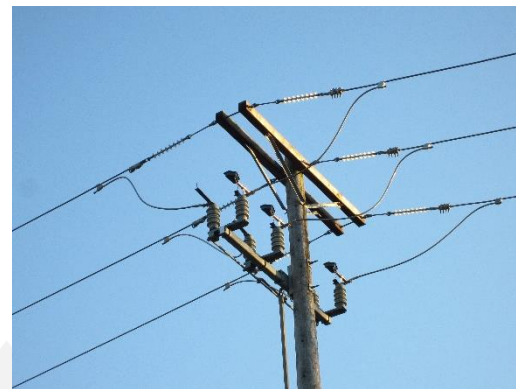
Automated Reconfiguration
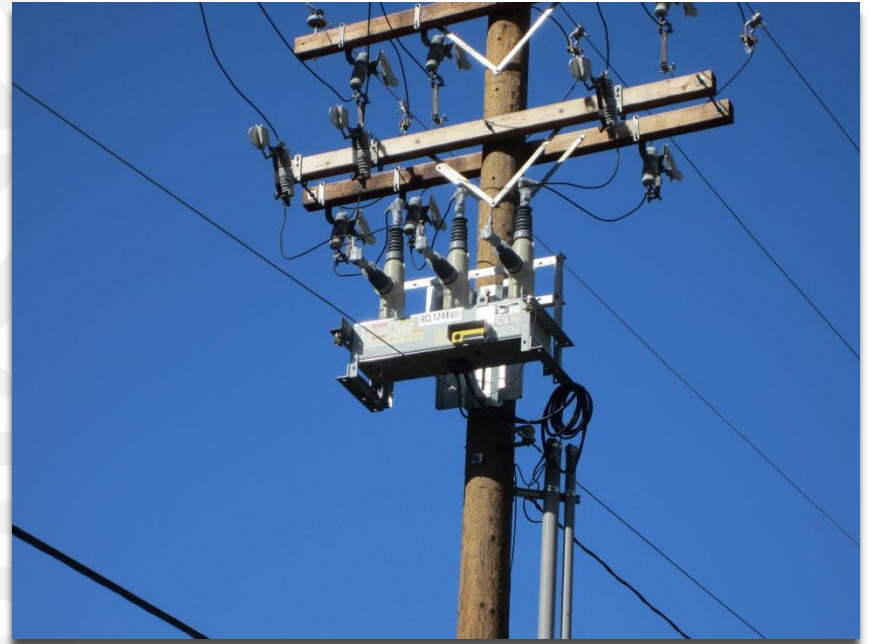
Switching Devices

► Switches

  ☐ Can be manually or remotely operated.

  ☐ Are not designed to interrupt load.

  ☐ Cannot be part of an automated reconfiguration scheme.

► Breaker/reclosers

  ☐ Can be manually or remotely operated.

  ☐ Are designed to interrupt load and fault currents.

 ☐ Can be connected to a SCADA system.

Fault Location, Isolation, and Service Restoration

► Auto-loop
  ◻ Recloser type devices operated in pre-defined teams.
  ◻ Static set points that can only respond to conditions within a predefined range.
 ◻ Can operate independently or connected to DMS.

► Adaptive Reconfiguration
  ◻ Recloser type devices operate in flexible configurations.
  ◻ Can operate independently or connected to DMS.
  ◻ Complex to operate and fully functional systems are still emerging.
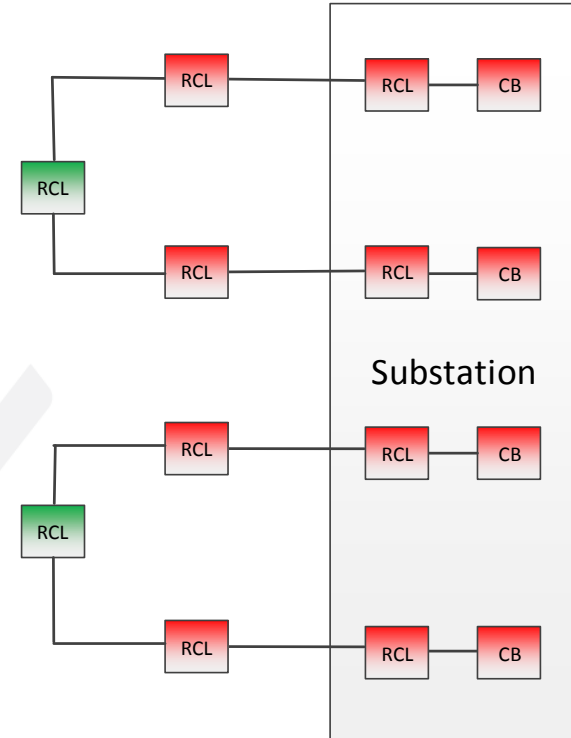
ADMS Applications

► 15 ADMS applications considered for review (DR, Short Circuit Analysis, DERMS, SOM, etc.)

► Four applications that are being evaluated:
  ☐ Volt-VAr Optimization (VVO)
  ☐ Fault Location Isolation & Service Restoration (FLISR)
 ☐ Online Power Flow (OLPF)/ State Estimation (DSSE)
  ☐ Market Participation
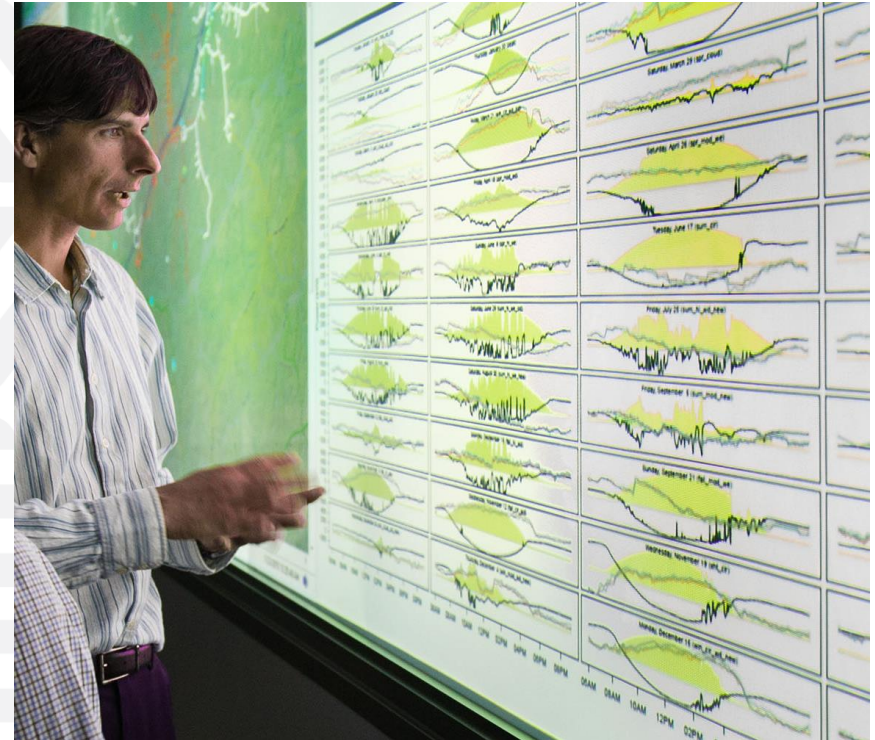
OLPF/DSSE Use Cases

► Model Improvement

  ◻ data needs for feeder models; specs and locations for adding new telemetry points; evaluate impact on ADMS applications

► Calibrate OLPF/DSSE functions

  ◻ Compare the states testbed measurements, tune algorithms

► Evaluate performance of hierarchical distributed sensing

  ◻ Integrating sensing technologies like AMI, OpenFMB, OpenADR, grid-edge smart controls, distribution PMUs

► Modeling loss of PV

  ◻ Behavior of behind-the-meter components (PV), net load allocation, integrate forecasting, customer facility data, load models, etc.

Volt-VAr Optimization (VVO) Use Cases

► Voltage Regulation

  ☐ legacy voltage control assets, smart inverters, energy storage, autonomous controllers

► Peak Load Management

  ☐ CVR for peak load management and interaction with "aggregators" like DERMS and DRAS

► Performance evaluation

  ☐ Multi-objective VVO, different control architectures

► Interaction with Active Grid Edge Devices
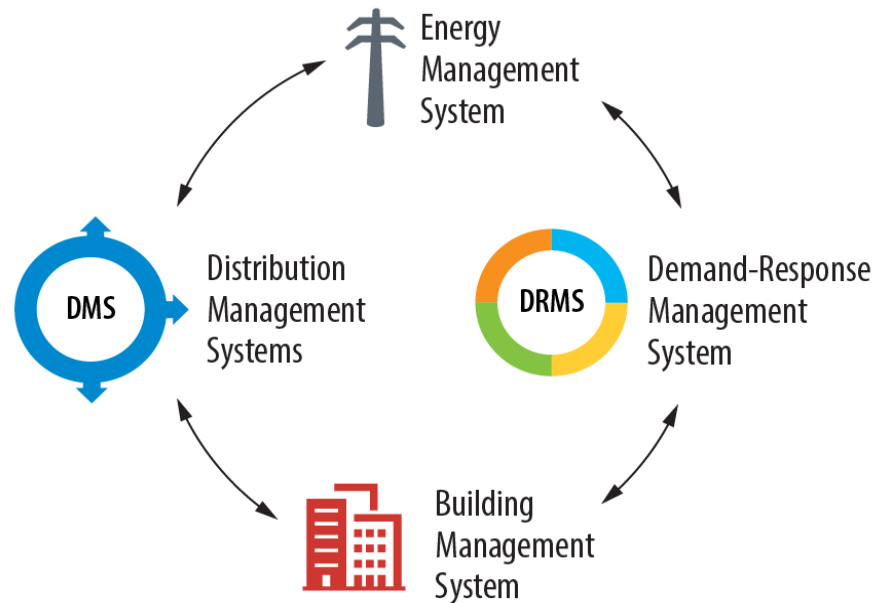
  ☐ Centralized VVO with grid-edge controllers
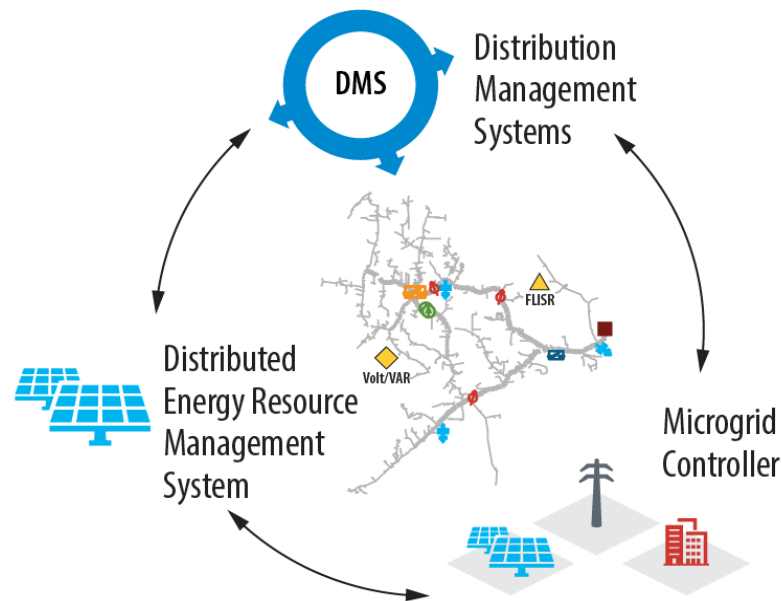
Fault Location Isolation & Service Restoration (FLISR) Use Cases

► High Penetration of DERs

  ☐ Upstream & downstream DERs; line loading before and after fault; intermittency & visibility challenges

► Interaction with Microgrids

  ☐ Impact of temporary fault, black start, need for direct comm

► Very High Loading Conditions

  ☐ Unnecessary backup feeder trip, Use of load forecasting

► Multiple Simultaneous Faults

  ☐ Thunderstorms leading to multiple faults, feeder re-tripping & lockouts

► Widespread Outages

  ☐ Uncertain distribution configurations, comm status and feeder outages

Market Participation Use Cases

► Maintaining power quality while providing bulk grid services

► Distribution System Operations (DSOs) providing market functions

► Estimating available capacity for bidding in energy markets

Energy Management System

Demand-Response Management System

DMS — Distribution Management Systems

DRMS

Building Management System

ADMS Case Studies

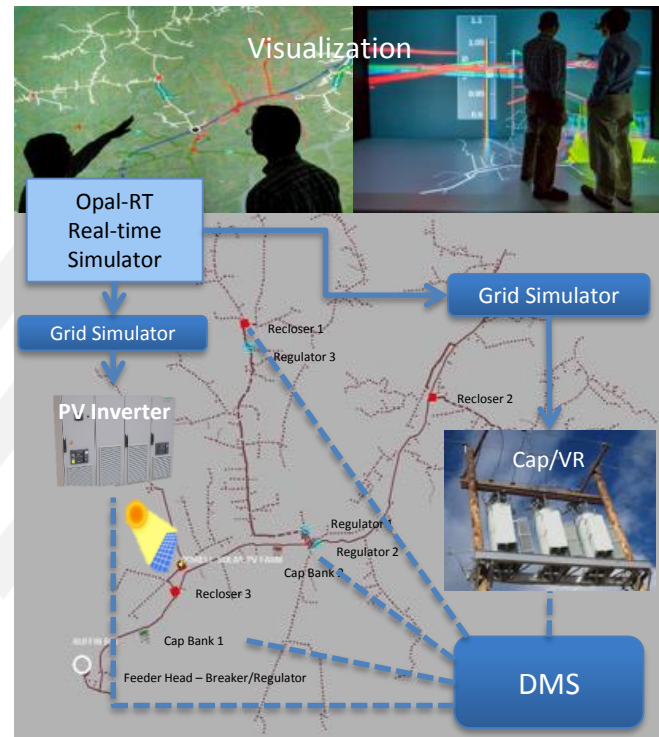# Case Study 1: Feeder Voltage using Advanced Inverters and a DMS
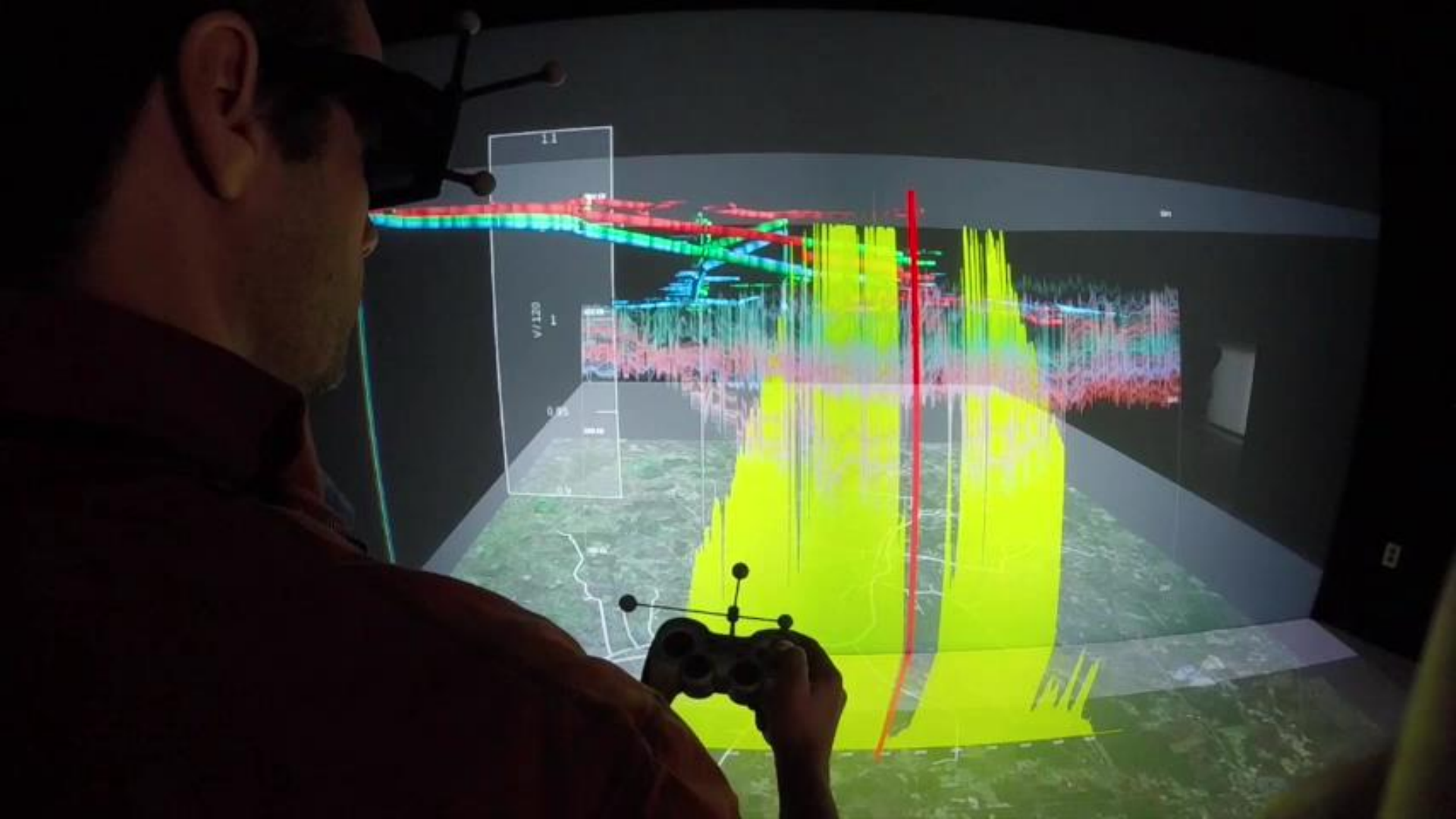
Objective:

Understand advanced inverter and distribution management system (DMS) control options for large (1–5 MW) distributed solar photovoltaics (PV) and their impact on distribution system operations for:

➢ Active power only (baseline);

➢ Local autonomous inverter control: power factor (PF) ≠1 and volt/VAR (Q(V)); and

➢ Integrated volt/VAR control (IVVC)

Approaches:

➢ Quasi-steady-state time-series (QSTS)

➢ Statistics-based methods to reduce simulation times

➢ Cost-benefit analysis to compare financial impacts of each control approach.


Palmintier, B., Giraldez, J., Gruchalla, K., Gotseff, P., Nagarajan, A., Harris, T., ... Baggu, M. (2016). Feeder Voltage Regulation With High Penetration PV Using Advanced Inverters and a Distribution Management System: A Duke Energy Case Study (NREL Technical Report No. NREL/TP-5D00-65551). Golden, CO: National Renewable Energy Laboratory.

Study System Characteristics

| Feeder Characteristics	
Substation primary/secondary voltage (kV LL)	44/13.5
Substation transformer (MVA/%X)	10/6.84
Feeder head gang-operated regulators, set of three (kVA/%X)	250/6.25 (each)
Feeder head X/R	4.25
$P(\text{Est. Native})_{\text{annual avg}}$ (MW)	1.71
$P(\text{Est. Native})_{\text{peak}}$ (MW and date)	5.26 (Jan. 30, 2014)
$P(\text{Measured})_{\text{annual avg}}$ (MW)	0.678
$P(\text{Measured})_{\text{min}}$ (MW)	-3.72
Capacitor Banks (number/total kVAR)	2/900
Line Regulator groups	1x3-phase, 2x2-phase
PV Plant Characteristics	
Commission date	March 2013
Plant rating (MW_{DC}/MW_{AC})	6.4/4.8
PV recloser X/R	1.82
Distance to substation (overhead line miles)	1.75
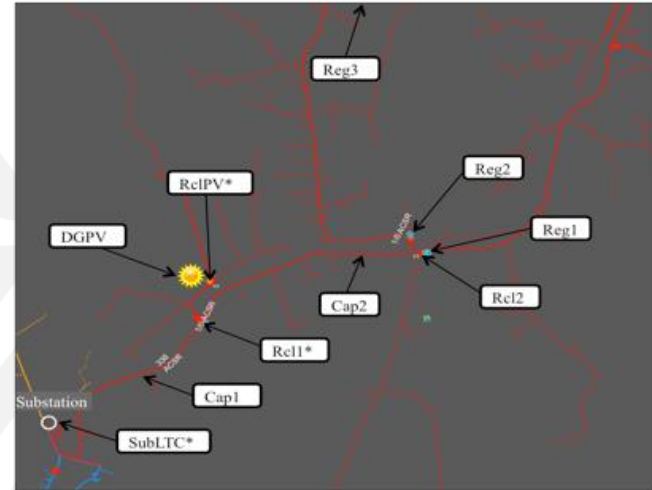
➢ Cap1: A 450-kVAR (150 kVAR per phase) VAR-controlled capacitor with temperature override. Cap2: A three-phase 450-kVAR capacitor (always disconnected unless controlled otherwise by IVVC)

➢ Reg1: A set of three single-phase 167-kVA regulators with a voltage target of 123

➢ Reg2: A set of two single-phase 114-kVA regulators on phase B and phase C with a voltage target of 123 V;

➢ Reg3: A second set of two single-phase 76.2-kVA regulators on phase B and phase C with a voltage target of 124 V;

Local Control Modes for the PV Inverter
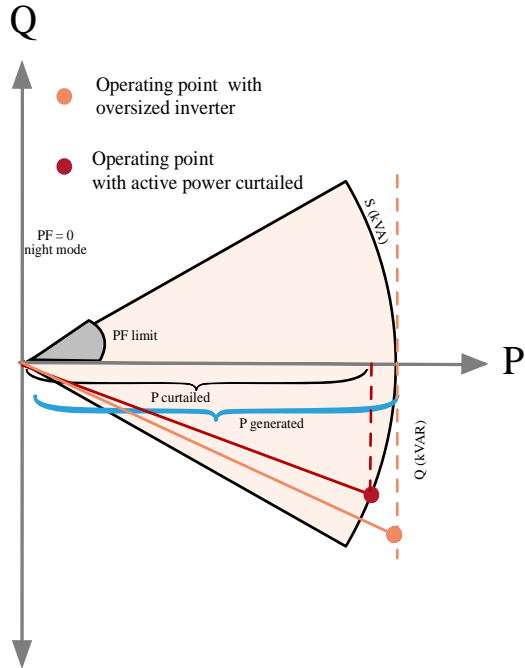

➤ **Constant Power Factor Set Point**

➤ **Volt/VAR Curves**
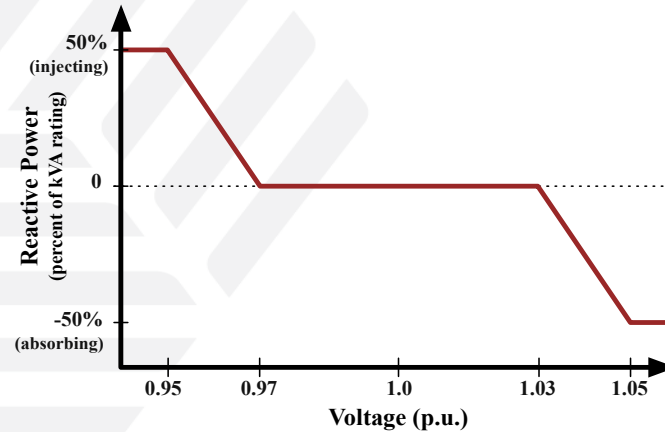
Data and Statistical Processing

➢ To capture the high ramp rates associated with the PV plant variability on the feeder and to generate accurate feeder statistics, a complete 1-minute data set (i.e., 525,600 measurements) for 2014 were provided

➢ Statistical smoothing to create native load

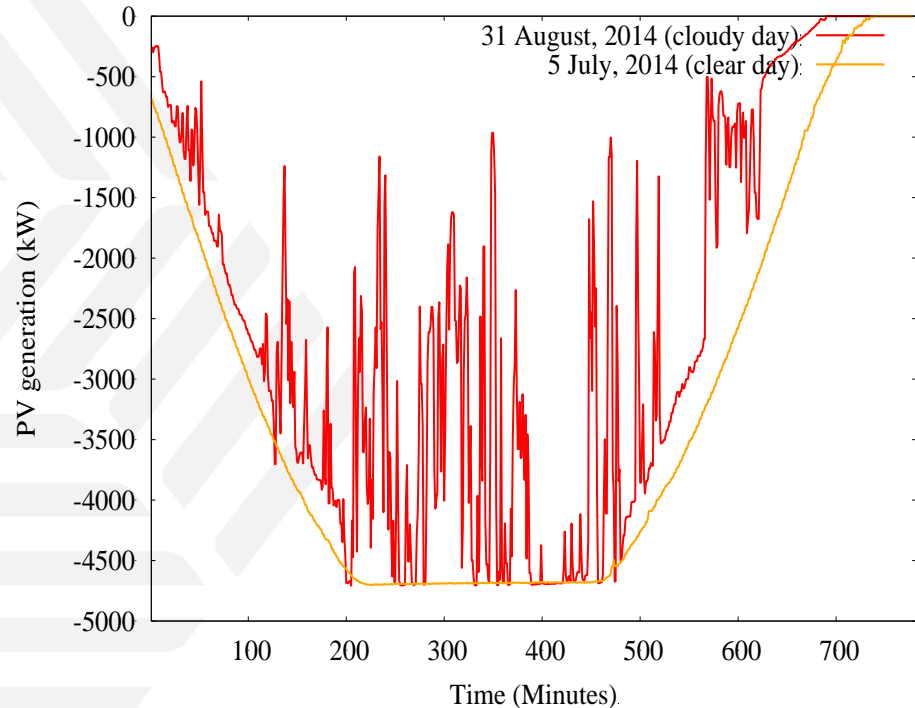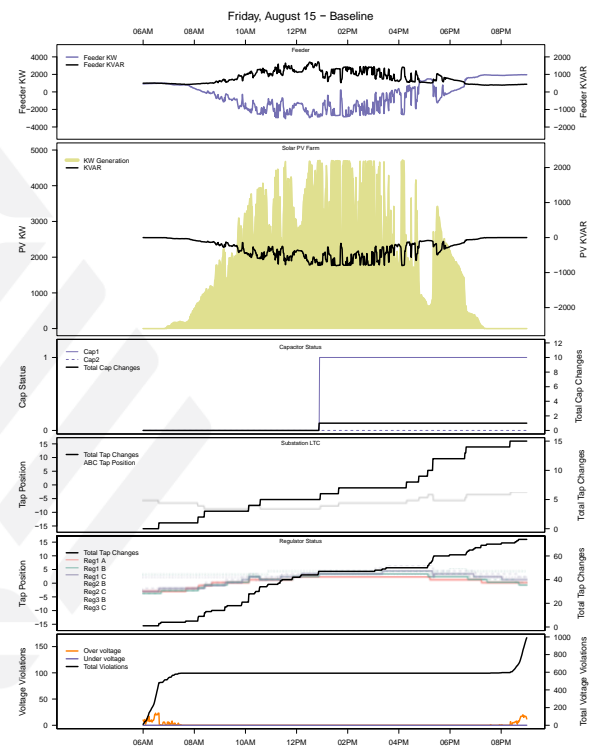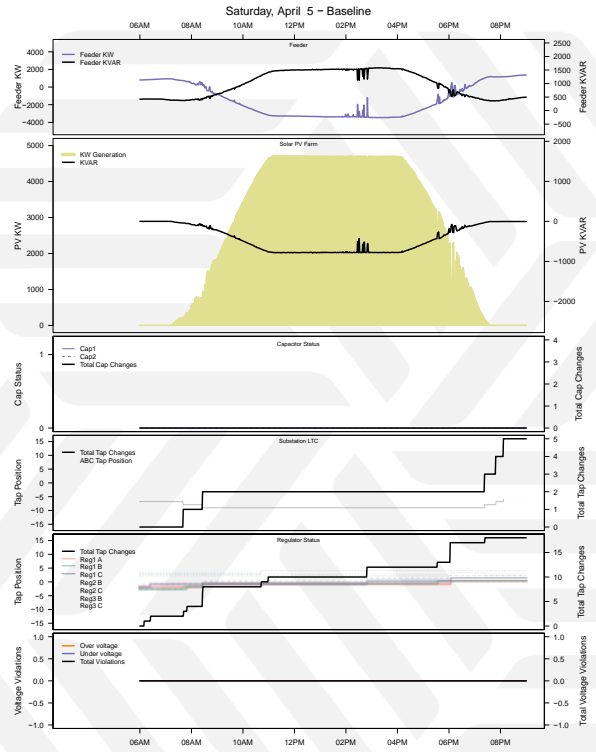| Equipment Name	Type	Measurement (All Three-Phase)	Interval: Range	Additional Interval: Range
Feeder	Feeder breaker	P, Q, I, V	1 min: 6 a.m.–9 p.m.	1 h: 24 h
RclPV (at PV Plant)	Recloser	P, Q, I, V	1 min: 6 a.m.–9 p.m.	1 h: 24 h
Rcl1	Recloser	P, Q, I, V	1 min: 6 a.m.–9 p.m.	1 h: 24 h
Rcl2	Recloser	P, Q, I, V	1 min: 6 a.m.–9 p.m.	1 h: 24 h
Cap1	Capacitor bank	State (tripped/close)	5 min: 24 h	
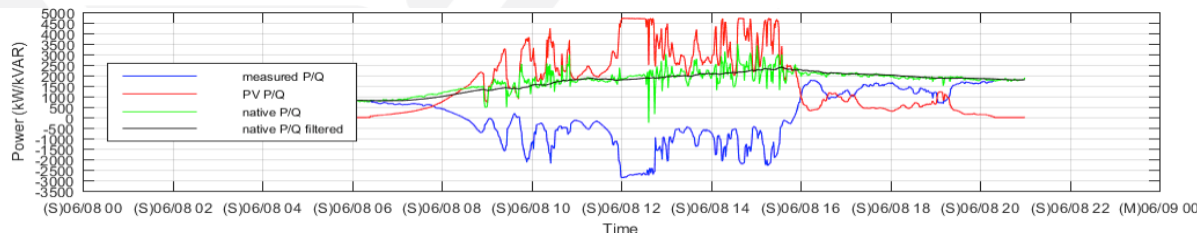
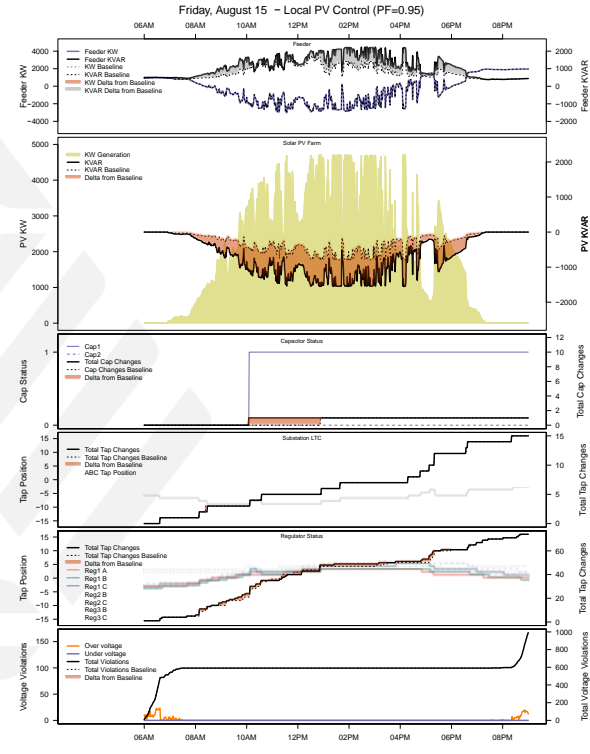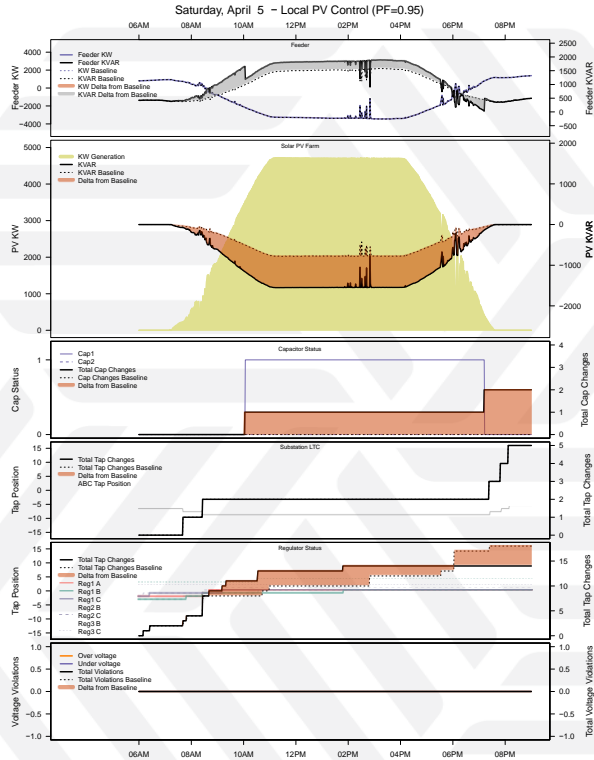# Data Analysis: 1 Year → 40 Days → 1 Year

October 2, 2017 | 28
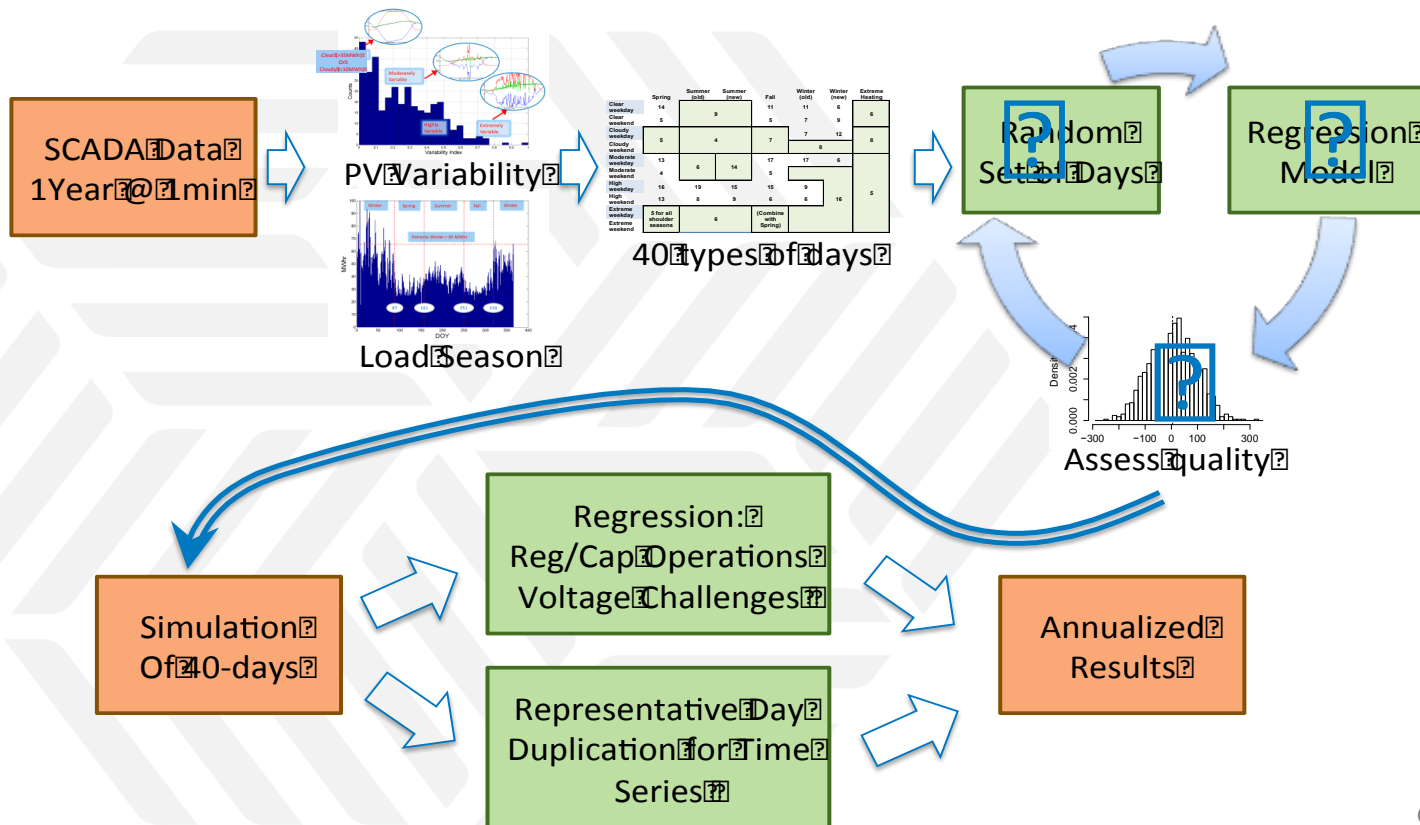
► Baseline

► Local PV Control (PF = 0.95)

► Local PV Control (Volt/VAR)

► Legacy IVVC (Exclude PV)
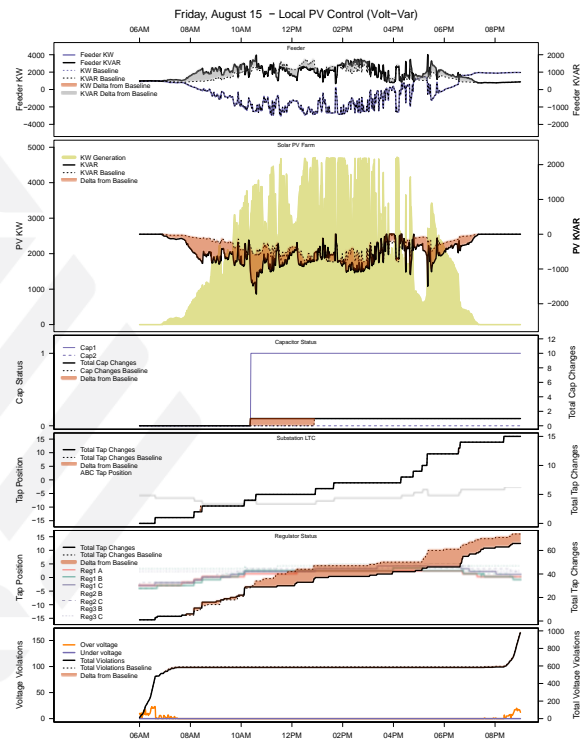
► IVVC with PV @ PF 0.95
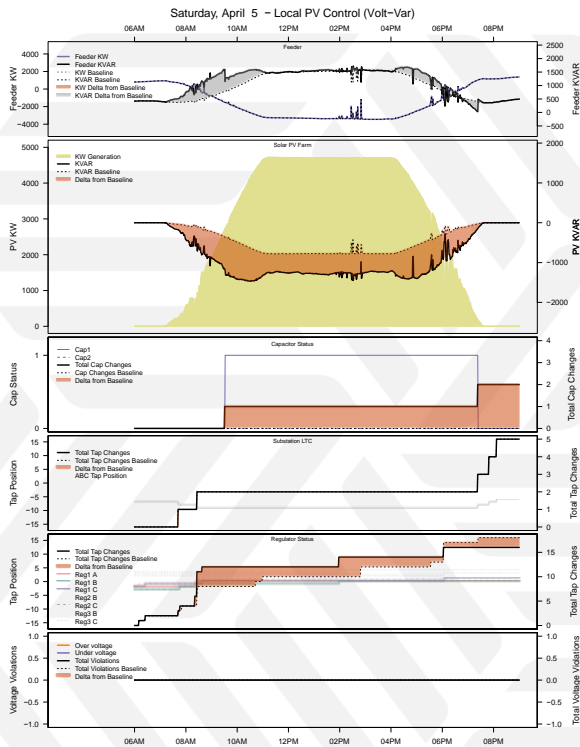
► IVVC (Central PV Control)

Baseline Results

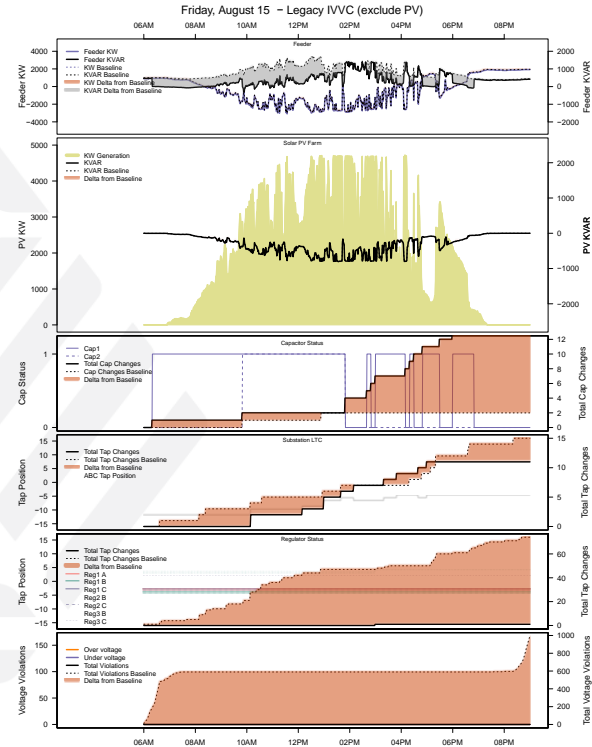# Autonomous Local Control

Local Volt/VAR Control

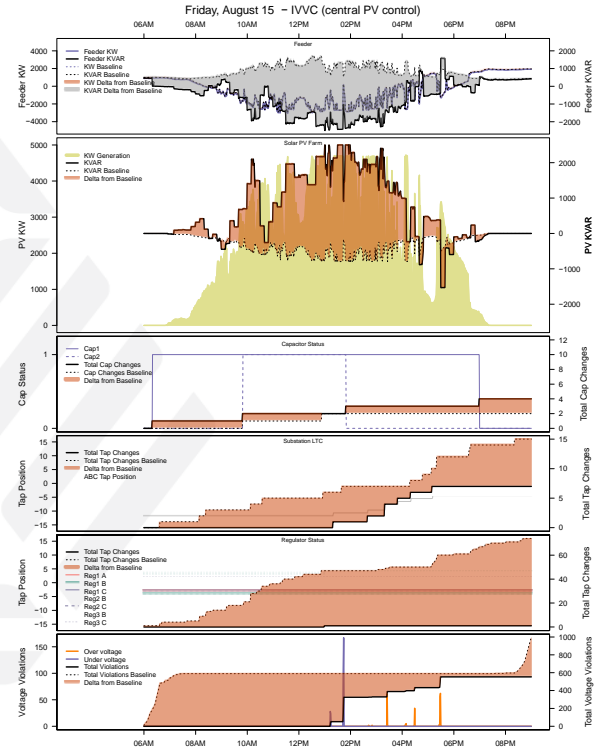Saturday, April 5 – Local PV Control (Volt–Var)
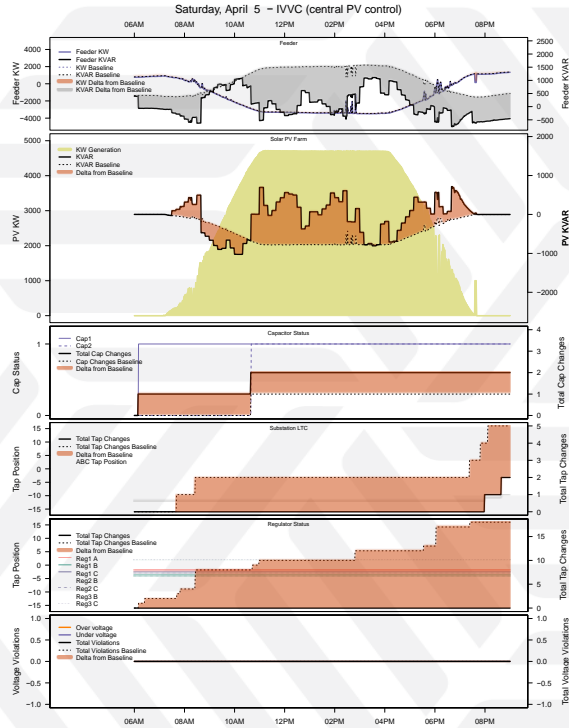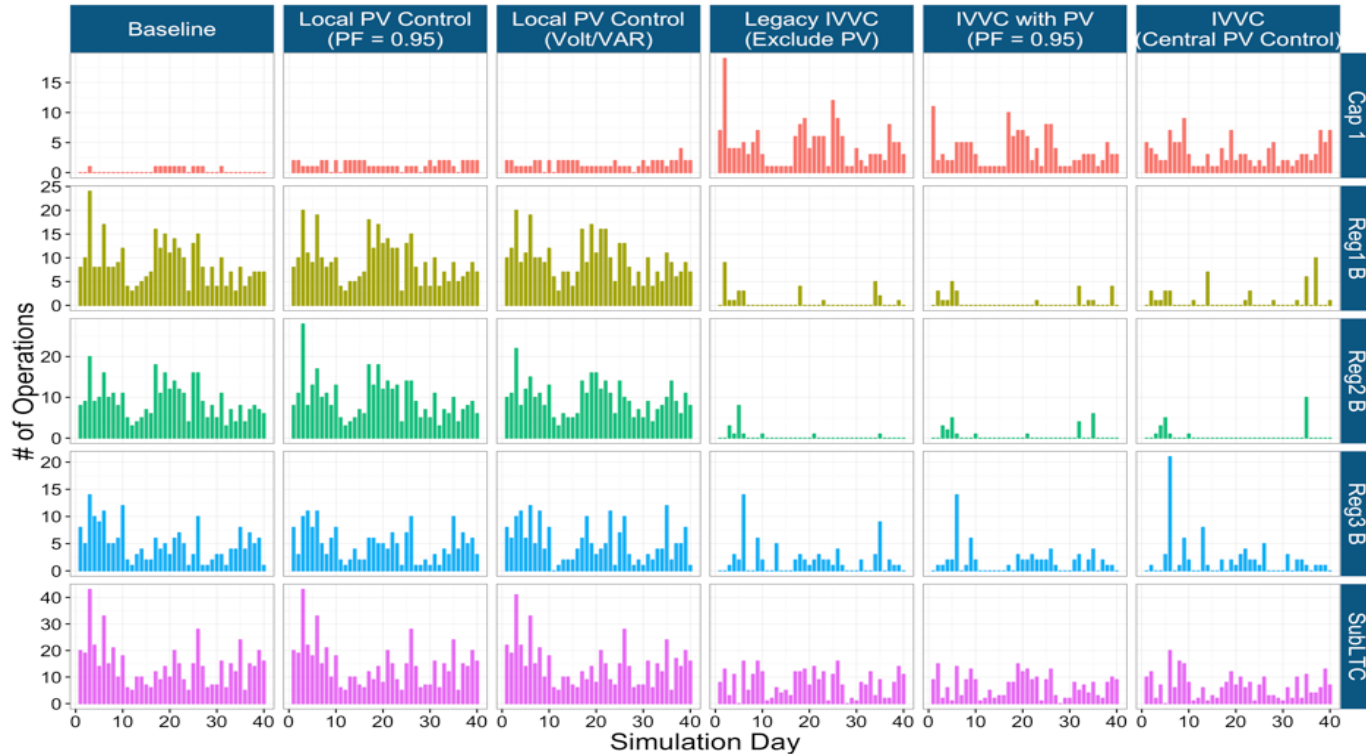
Friday, August 15 – Local PV Control (Volt–Var)

Legacy DMS Integrated Volt/VAR Control with LTC, VR and Caps Only
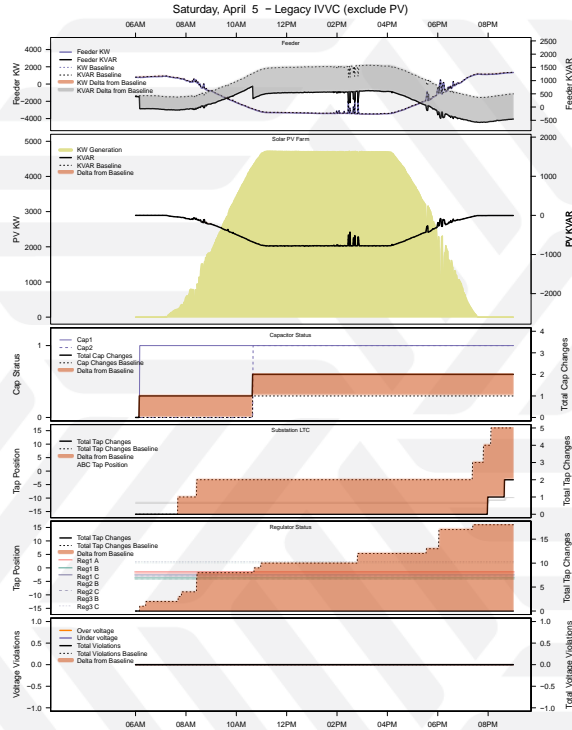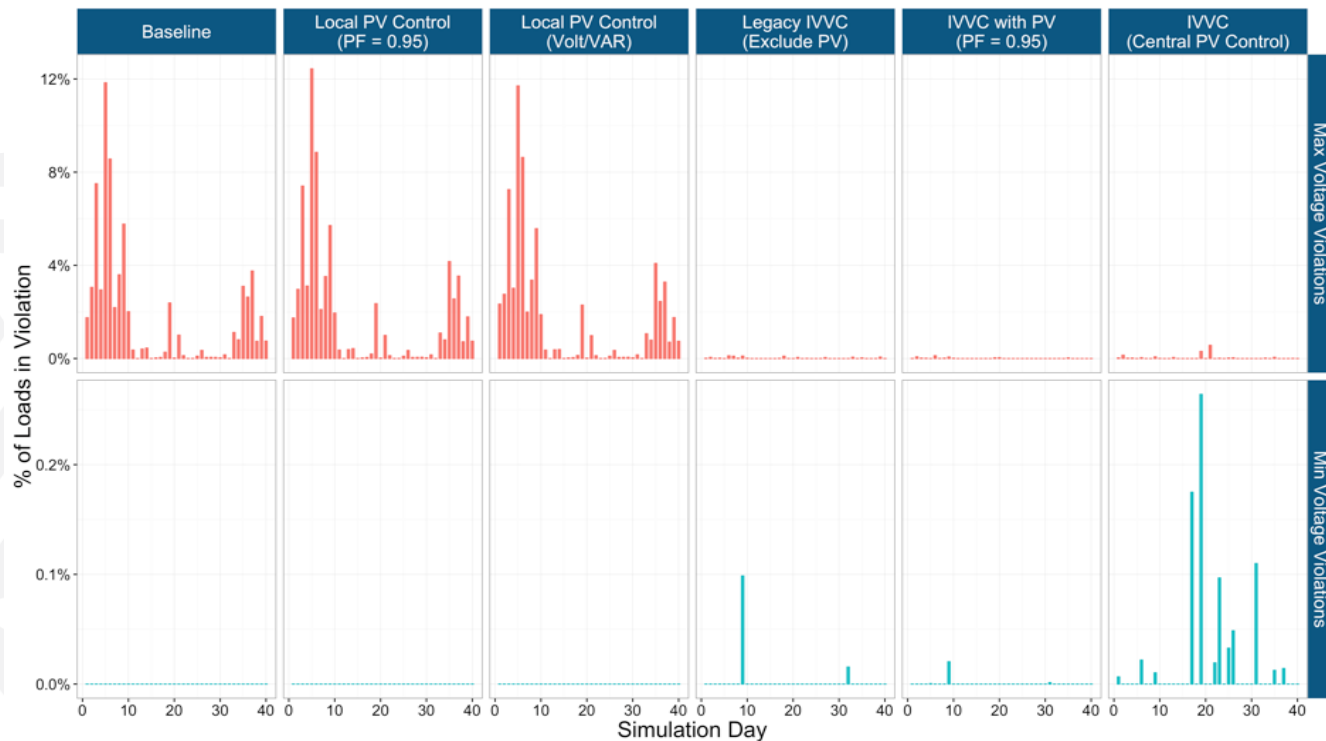
Integrating Advanced Inverters into IVVC

Feeder 40-day results of number of operations of voltage regulation equipment

Feeder 40-day results of number of load-voltage violations

Summary Comparison of Annualized Scenarios

Scenario	PV Mode	IVVC Control				Annualized Equipment Operations				Voltage Challenges	
		LTC	Regulators	Capacitors	PV	LTC	Regulators	Capacitors	Total	Over	Under
Baseline	Default	-	-	-	-	5,043	19,160	125	24,328	1.47%	0.00%
Local PV Control (PF = 0.95)	PF=0.95	-	-	-	-	5,063	19,943	505	25,511	1.48%	0.00%
Local PV Control (Volt/VAR)	Q(V)	-	-	-	-	5,087	19,857	541	25,485	1.44%	0.00%
Legacy IVVC (Exclude PV)	Default	Y	Y	Y	-	2,869	2,943	1,863	7,675	0.02%	0.00%
IVVC with PV (PF = 0.95)	PF=0.95	Y	Y	Y	-	2,498	1,888	1,409	5,795	0.01%	0.00%
IVVC (Central PV Control)	IVVC for reactive power	Y	Y	Y	Y	2,312	2,698	1,151	6,161	0.05%	0.02%

Substation P/Q Plots
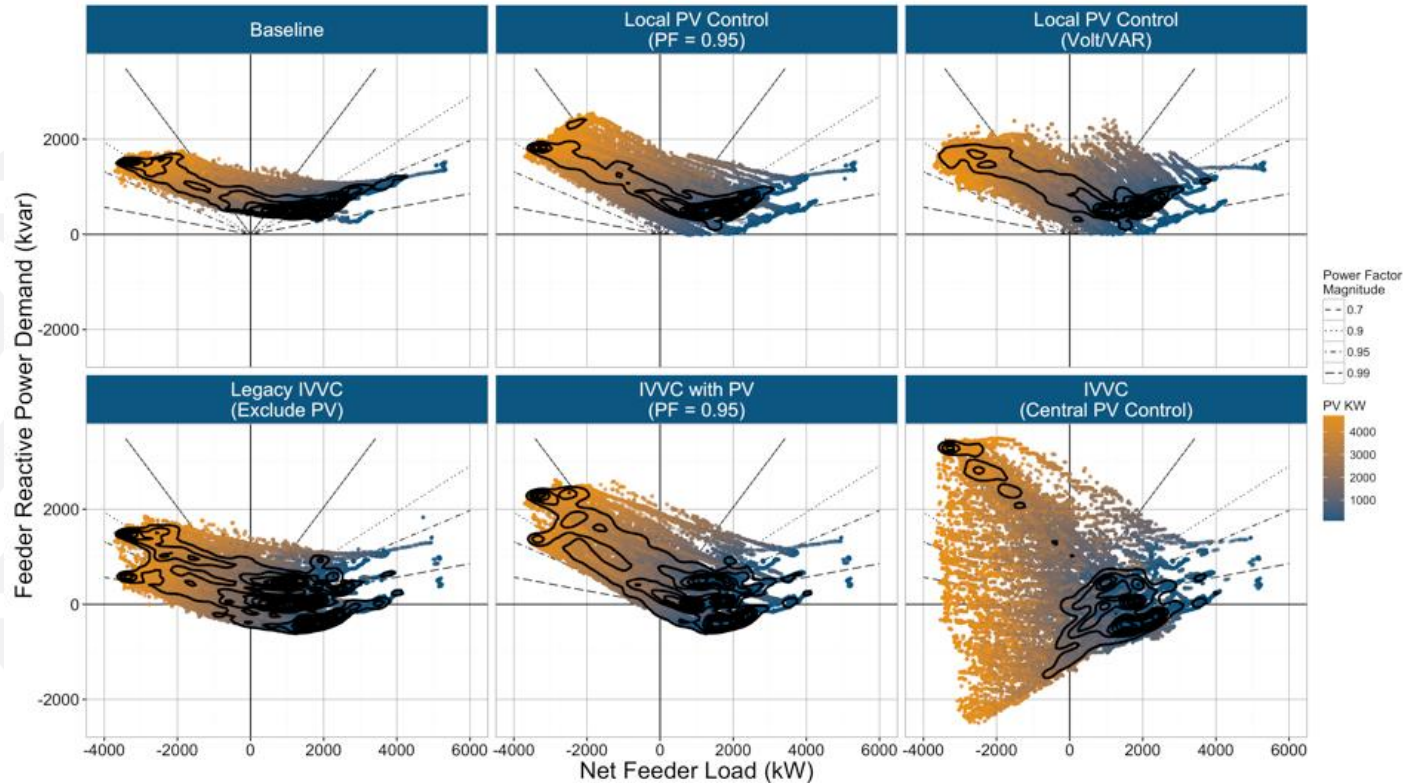
Cost-Benefit Analysis Assumptions

```
┌─────────────┐      ┌─────────────┐
│  Calculate  │      │ Extrapolate │
│  Commodity  │ ───► │Last Simulated│
│Value Streams│      │ Year Values │
└─────────────┘      └─────────────┘
```

Value Streams: PV energy production, feeder losses, loads, and the frequency of operation of switching equipment with the expected resulting requisite maintenance and replacement expenditures

```
┌─────────────┐      ┌─────────┐      ┌─────────┐      ┌─────────────┐      ┌─────────────┐
│Apply Annual │      │  Apply  │      │  Apply  │      │ Accumulate  │      │Cross-tabulate│
│ Capital and │ ───► │Inflation│ ───► │Discounting│ ──►│ Discounted  │ ───► │  (pivot) and │
│ Non-Capital │      │         │      │         │      │ Cash Flows  │      │Present Results│
│ Unit Costs  │      └─────────┘      └─────────┘      └─────────────┘      └─────────────┘
└─────────────┘
```

| Dates	Days of Week	Times	Value of Energy (¢ per kWh)	
			Capacity Credit	Energy Credit
June 1–Sept. 30	M–F	Summer on-peak: 1 p.m.–9 p.m.	6.00	3.87
		Summer off-peak: 9 p.m.–1 p.m.		3.33
	Sun. & Sat.	Summer off-peak: All		3.33
Oct. 1–May 31	M–F	Winter on-peak: 6 a.m.–1 p.m.	2.19	3.87
		Winter off-peak: 1 p.m.–6 a.m.		3.33
	Sun. & Sat.	Winter off-peak: All		3.33

Cumulative NPV's and Aggregated cumulative discounted cash flows for equipment replacement
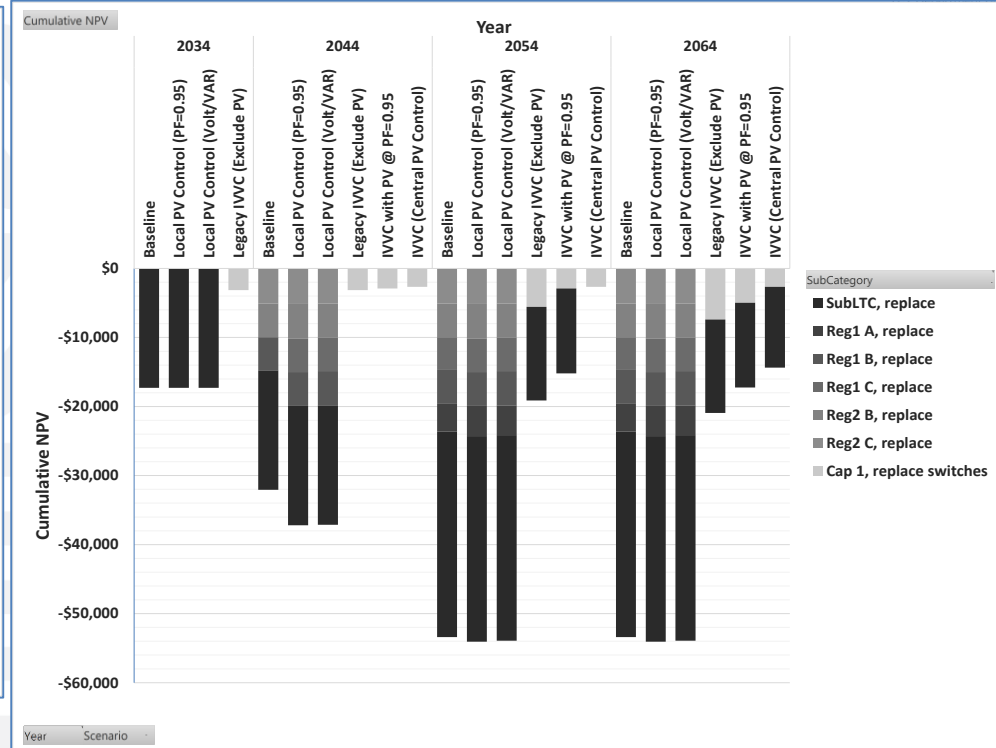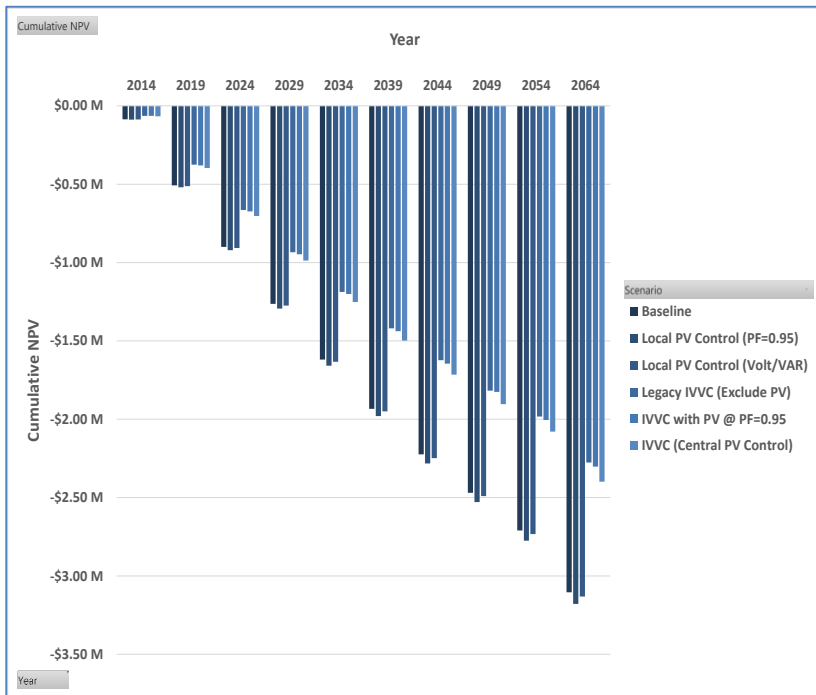
Categorical Cost and Savings
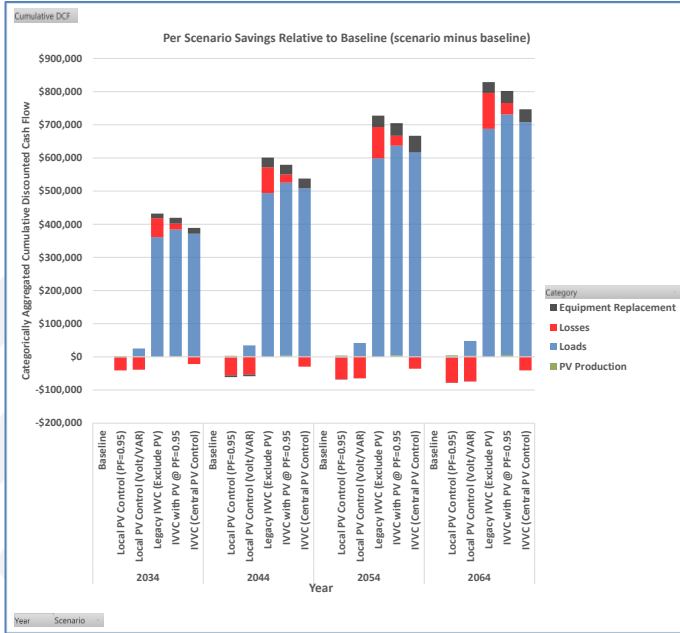
Categorical cost and savings compared to baseline
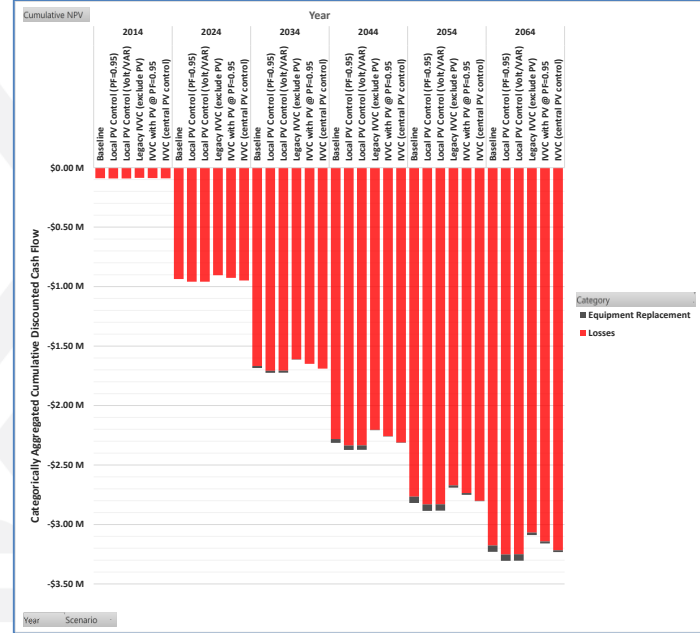
Categorically aggregated cumulative discounted cash flows for costs of feeder losses and equipment replacement

Case Study 1: Conclusion

► This work Illustrates the potential for coordinated control of voltage management equipment, such as the central DMS-controlled IVVC by:

- Providing substantial improvement in distribution operations with large-scale PV systems
- reducing regulator operations
- Decreasing the number of voltage challenges

► The preliminary cost-benefit analysis showed operational cost savings for the IVVC scenarios that were:

- partially driven by reduced wear and tear on utility regulating equipment,
- but dominated by the use of CVR/Demand reduction objective

► Work needed in the area of integrating advanced inverters as controllable resources into IVVC optimization strategies

- Event triggered operation of DMS IVVC
- Power factor set point in place of reactive power set point

Thank you

Questions?

Backup slides

Case Study 2: Voltage Support Using Smart PV Inverters

AMI-1 (Near PV Systems)

OpenDSS model

AMI-2 (Near Substation)

- AMI
- Transformer
- capacitor
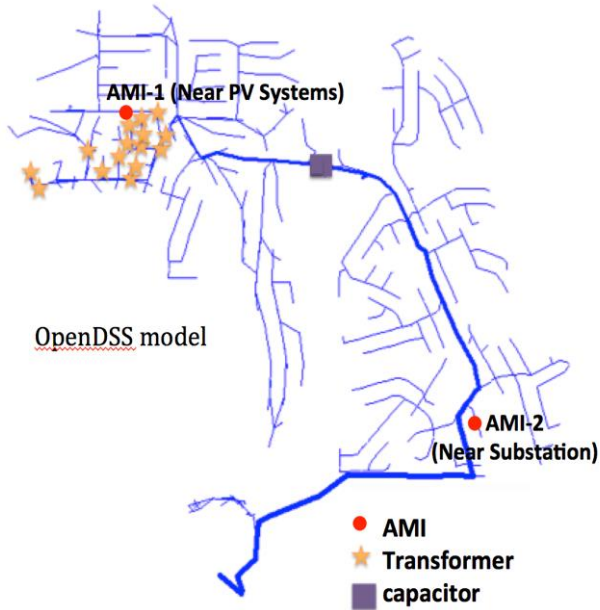
F. Ding, A. Pratt, T. Bialek, F. Bell, M. McCarty, K. Atef, A. Nagarajan and P. Gotseff, "Voltage support study of smart PV inverters on a high photovoltaic penetration utility distribution feeder," in IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, June 2016.

- 2040 nodes, serving ~4.15 square miles.
- Peak load = 9.89MW
- One controllable 1200 kVAr capacitor: switch on at 6 am, switch off at 10 pm
- ~1 MW existing PV power with standard inverters (~10% penetration)
- ~700 kW planned PV with smart inverters (~7% penetration)
- ~500 kW planned PV with standard inverters (~5% penetration)
- Planned PV Systems are distributed at 16 service transformer locations.

Voltage Impact Analysis

- **Maximum Load Day**
- **Minimum Load Day**
- **Clear Day**
- **Cloudy-Intermittent Day**
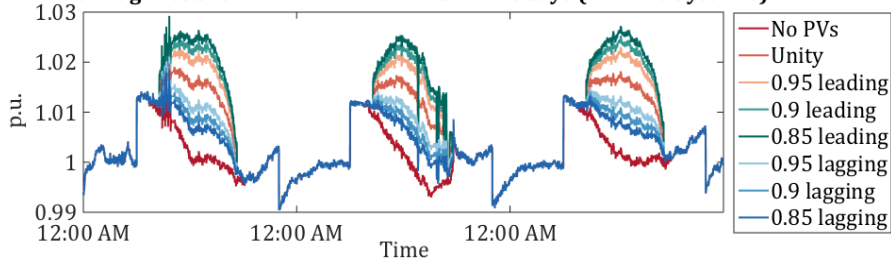- **PV Intermittent Day**

For each type of day, simulated:
- Unity power factor
- Six fixed power factors:
  - 0.95, 0.9, 0.85 leading
  - 0.95, 0.9, 0.85 lagging
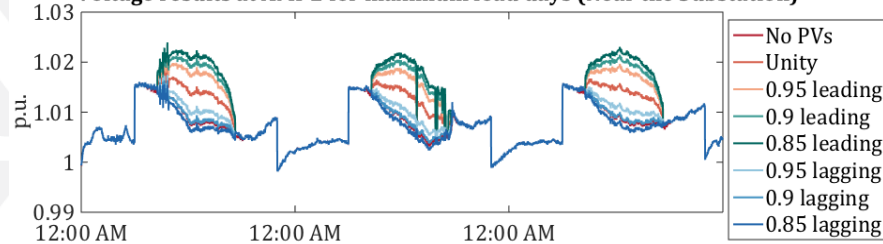- Three Volt/VAr curves
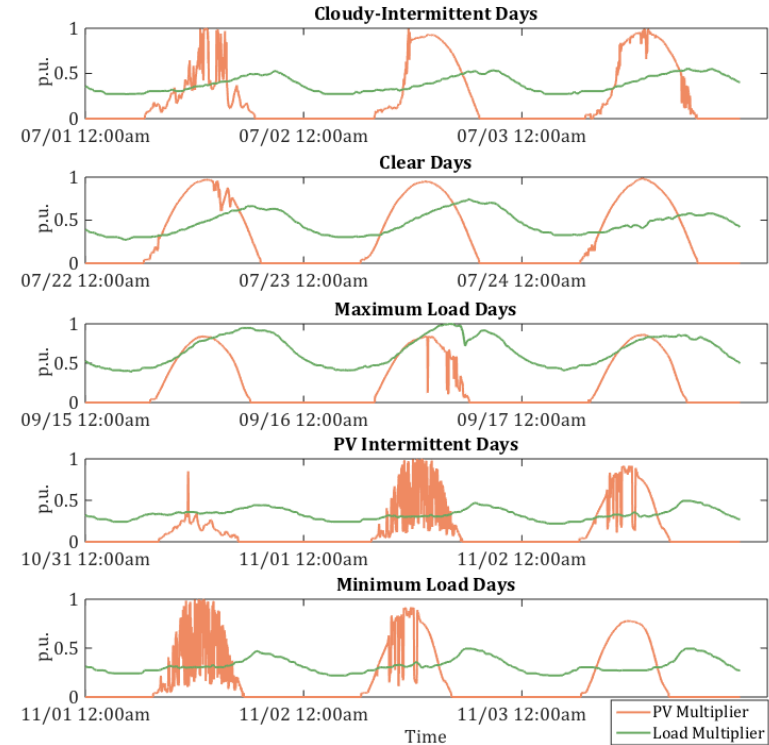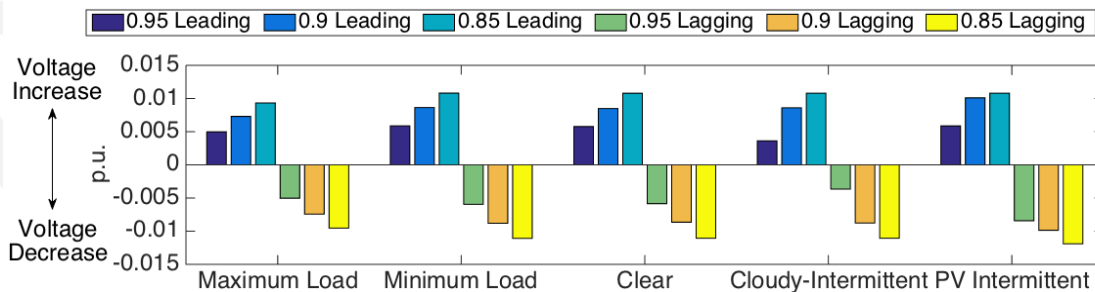
Voltage Impact Analysis: Fixed Power Factors

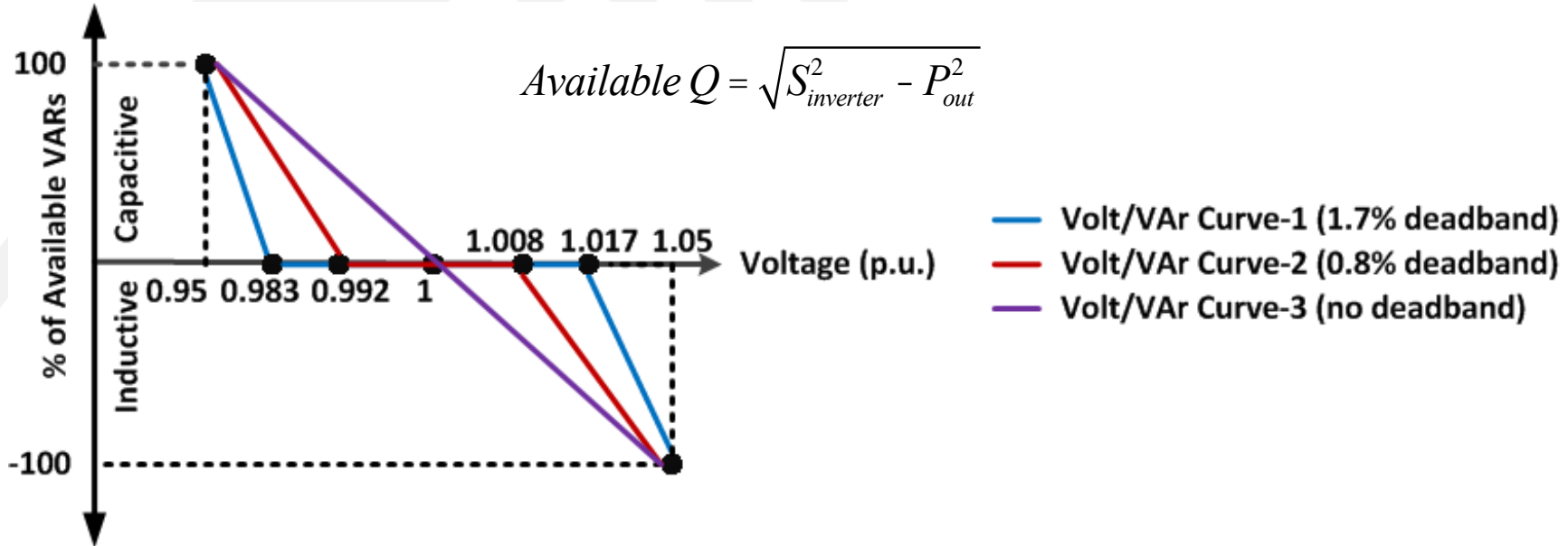**Voltage results at AMI-1 for maximum load days (Near PV Systems)**

Legend: No PVs, Unity, 0.95 leading, 0.9 leading, 0.85 leading, 0.95 lagging, 0.9 lagging, 0.85 lagging

Voltage results at AMI-2 for maximum load days (Near the Substation)

Legend: No PVs, Unity, 0.95 leading, 0.9 leading, 0.85 leading, 0.95 lagging, 0.9 lagging, 0.85 lagging

Maximum voltage change throughout the feeder under different fixed power factors for each type of days.

Legend: 0.95 Leading, 0.9 Leading, 0.85 Leading, 0.95 Lagging, 0.9 Lagging, 0.85 Lagging

X-axis categories: Maximum Load, Minimum Load, Clear, Cloudy-Intermittent PV Intermittent

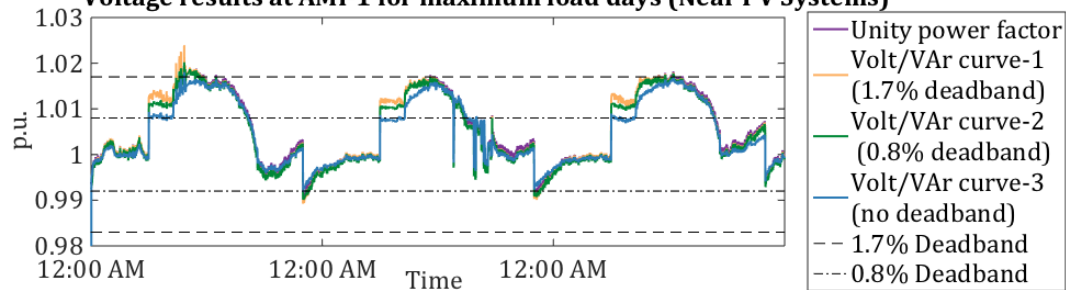$$Available\ Q = \sqrt{S_{inverter}^2 - P_{out}^2}$$
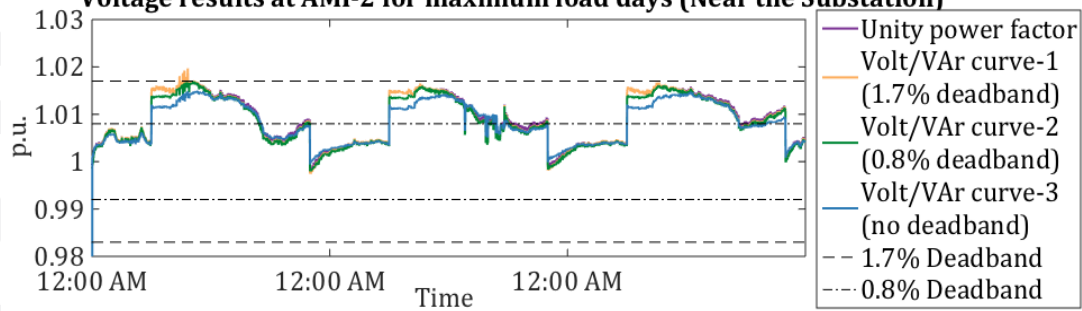
Voltage Impact Analysis: Volt/VAr Control

Maximum load days: Voltage Results at Two AMI locations

The voltage range (maxV-minV) was reduced the most with Volt/VAr curve-3: by 0.007 p.u. (22%) at AMI-1 and by 0.006 p.u. (28%) at AMI-2.
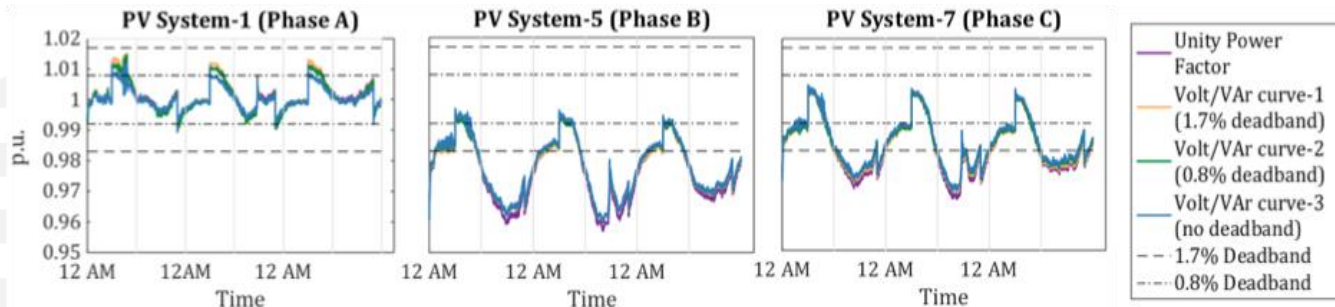

Voltage results at AMI-1 for maximum load days (Near PV Systems)

Legend:
- Unity power factor
- Volt/VAr curve-1 (1.7% deadband)
- Volt/VAr curve-2 (0.8% deadband)
- Volt/VAr curve-3 (no deadband)
- 1.7% Deadband
- 0.8% Deadband

Voltage results at AMI-2 for maximum load days (Near the Substation)

Legend:
- Unity power factor
- Volt/VAr curve-1 (1.7% deadband)
- Volt/VAr curve-2 (0.8% deadband)
- Volt/VAr curve-3 (no deadband)
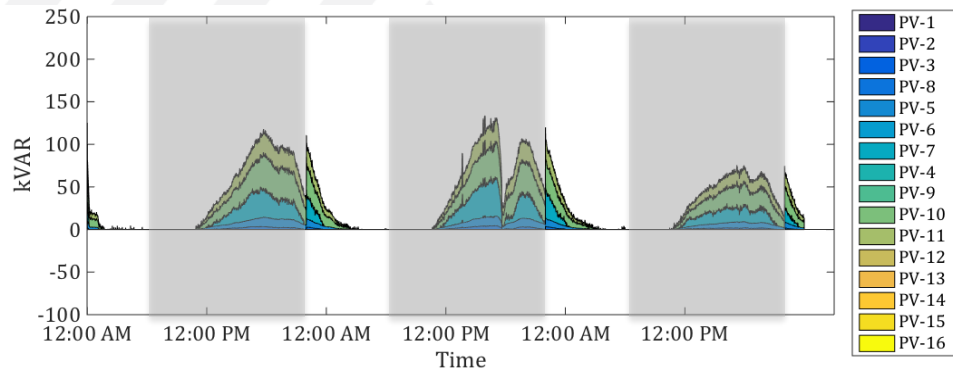- 1.7% Deadband
- 0.8% Deadband

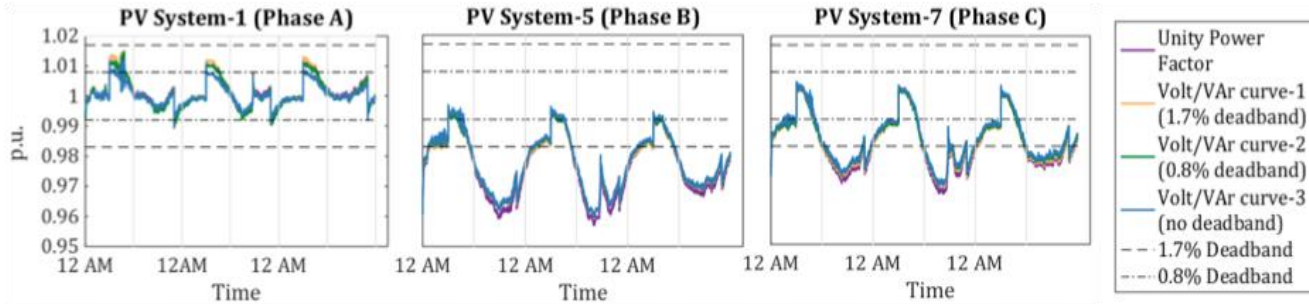# Voltage Impact Analysis: Reactive Power Output

Terminal voltages of three representative smart inverters, one for each phase.

- At Phase A: PV systems 1, 2, 3, 4, 6, 9, 12, 13, 14, 15, 16.
- At Phase B: PV systems 5, 10, 11.
- At Phase C: PV systems 7, 8.

Reactive Power Output:
Volt/VAr Curve-1
Max Qtotal = 134 kVAr

Voltage Impact Analysis: Reactive Power Output

Reactive Power Output:
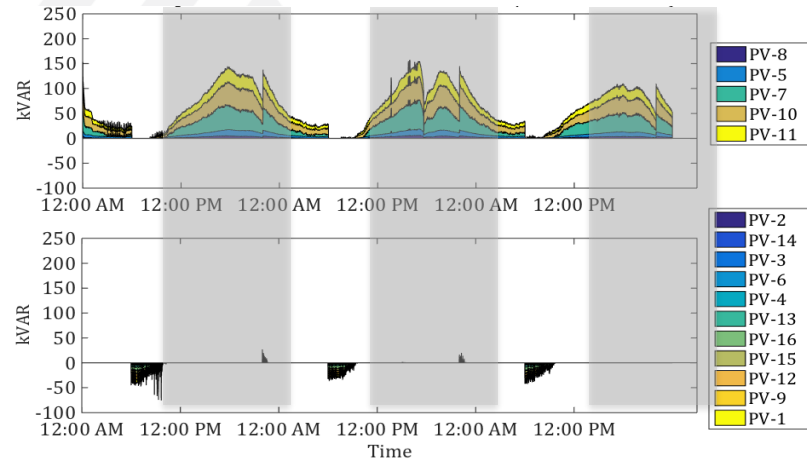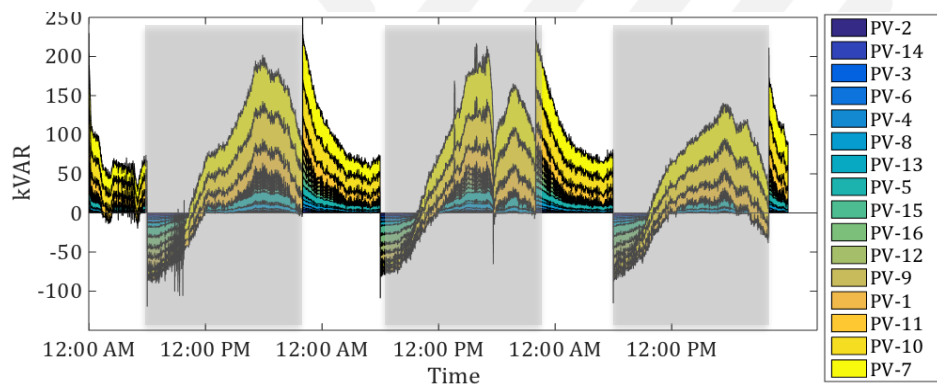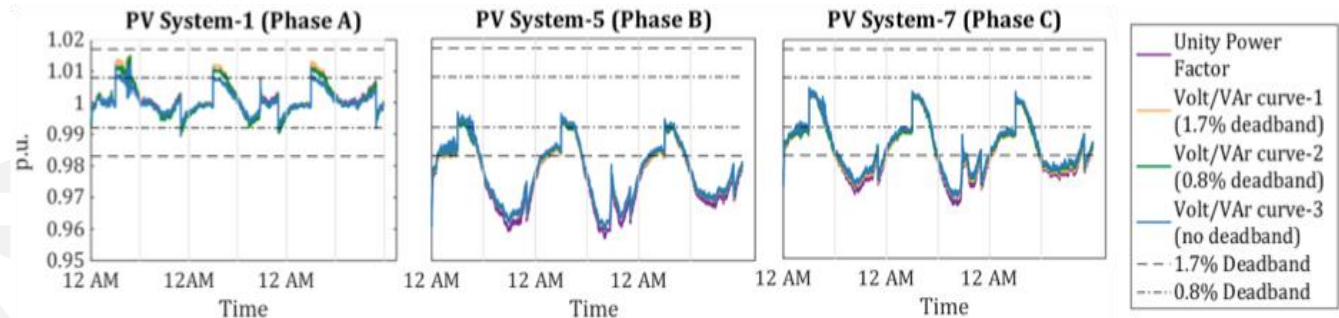**Volt/VAr Curve-2**

Max Qtotal = 150 kVAr

Voltage Impact Analysis: Reactive Power Output

Reactive Power Output: Volt/VAr Curve-3

Max Qout = 250 kVAr (33% of rated kVA rating)

Voltage Impact Analysis: Statistics Summary
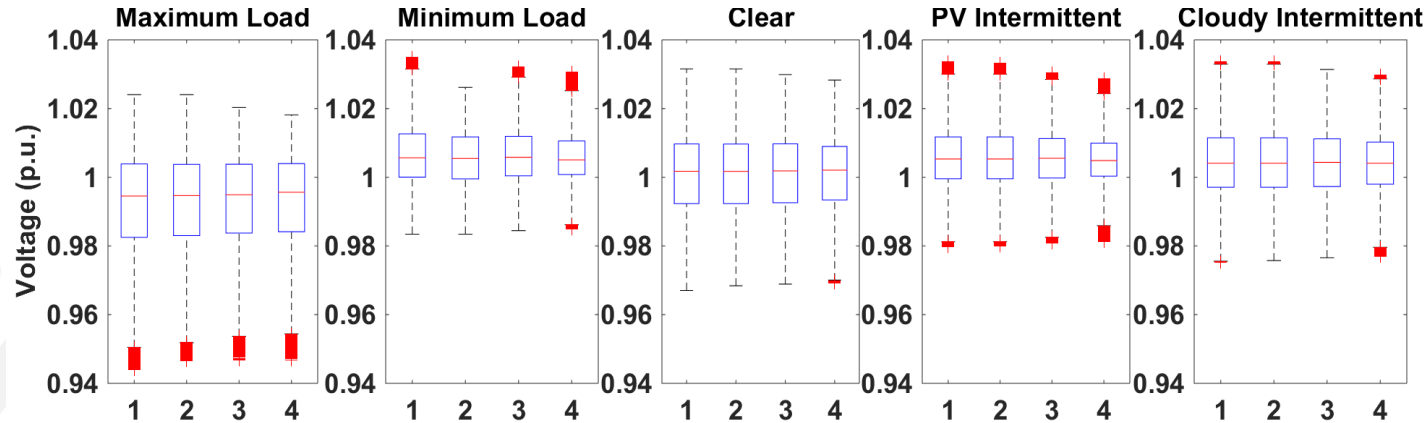
Voltage range and standard deviation for 1) unity power factor, 2) Volt/VAr curve-1, 3) Volt/VAr curve-2, and 4) Volt/VAr curve-3. Data in red indicate values beyond 1.5 times the interquartile range.

- Voltage range reduced by up to 0.009 p.u. (11%) on maximum load days.
- Standard deviation reduced by up to 0.002 p.u. (23%) on minimum load days.

"Tighter" Voltage Profile

Case Study 2: Conclusion

- Results from a specific utility feeder:
  - Fixed 0.85 power factor → **change in primary voltage** just over 1%
    - 700 kW of PV with smart inverters had comparable voltage impact to 1,200 kVAr switched capacitor
  - Volt/VAr → reduced **range** and **standard deviation** of voltages
    - No deadband had most significant voltage profile improvement
    - Reduced voltage range up to 11%; standard deviation up to 23 %

Conservation of Voltage Reduction

Conservation of Voltage Reduction (CVR): *A voltage reduction scheme that flattens and lowers the distribution system voltage profile to reduce overall energy consumption.*
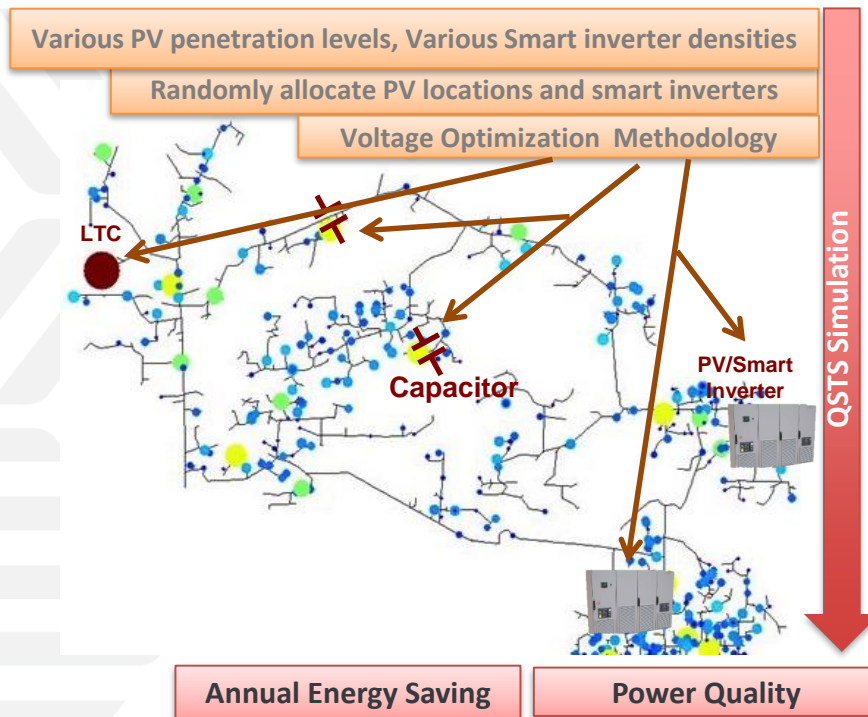
- Works best with resistive and constant impedance loads
- Normally performed by flattening the system voltage using capacitor banks and/or voltage regulators and lowering the voltage by controlling a substation Load Tap Changer
- Also performed by using a central volt/VAR optimization performed by a distribution management system (DMS)
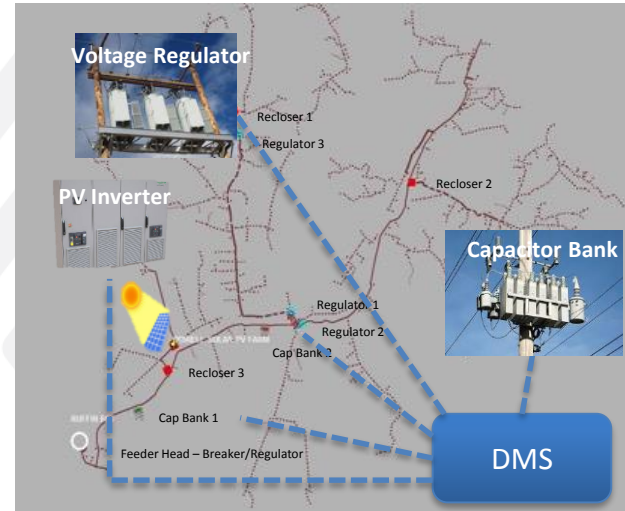
Case Study 3: Smart Inverter Volt-VAR Function for CVR and Power Quality

Objective: Evaluate the effects of distributed PV with smart inverters on the conservation of voltage reduction (CVR) energy savings and power quality in distribution systems.

F. Ding *et al*., "Application of Autonomous Smart Inverter Volt-VAR Function for Voltage Reduction Energy Savings and Power Quality in Electric Distribution Systems," *IEEE* Innovative Smart Grid Technologies , Washington DC, 2017.


Various PV penetration levels, Various Smart inverter densities

Randomly allocate PV locations and smart inverters

Voltage Optimization Methodology

LTC

Capacitor

PV/Smart Inverter

QSTS Simulation

Annual Energy Saving

Power Quality

Voltage Reduction Optimization Method

- **Energy saving is used to measure the voltage reduction effect:**

$$VRsaving = \frac{Energy_{VR} - BaseEnergy_{noVR}}{BaseEnergy_{noVR}} \times 100\%$$

- **CVR factor (the percentage change in energy consumption per percent change in the load's voltage):** 0.8 (real) and 4.0 (reactive)
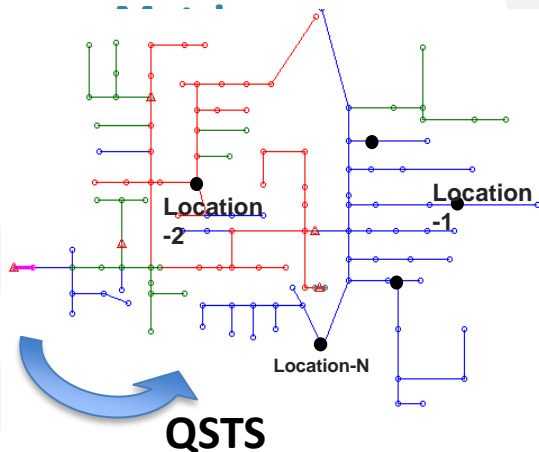
- Capacitor Optimization: flattest voltage
- LTC Optimization: adjust LTC tap position to achieve the lowest voltage
- Autonomous Smart Inverter Volt-VAR Control

Power Quality Scoring Methodology

◆ **Power Quality**

Location -2

Location -1

Location-N

QSTS
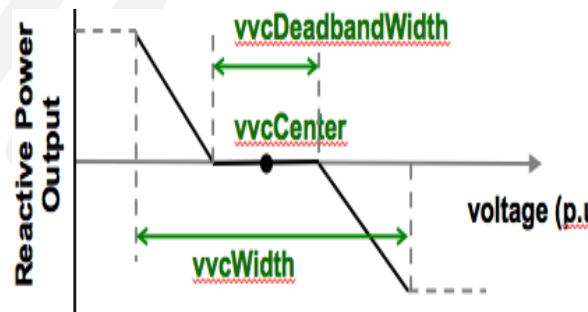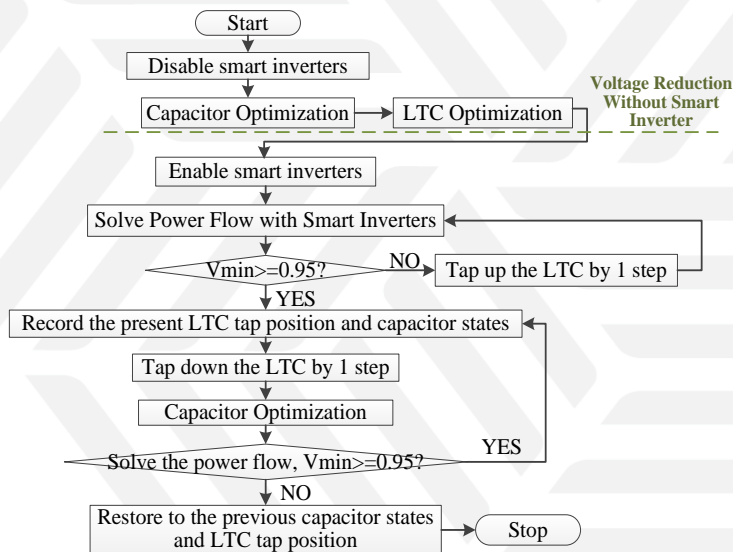
- **System Average Voltage Magnitude Violation Index (SAVMVI):** *average value of all voltage magnitude violations for all buses at all time steps.*

$$SAVMVI = \frac{1}{N}\left[\frac{1}{T}\sum_{i=1}^{N}\sum_{t=1}^{T}VIO_{Vmag}^{i}(t)\right]$$

- **System Average Voltage Fluctuation Index (SAVFI):** *average value of voltage fluctuations for all buses at all time steps.*
- **System Average Voltage Unbalance Index (SAVUI):** *average value of voltage unbalances for all three-phase buses at all time steps.*
- **System Control Device Operation Index (SCDOI):** *total number of capacitor switching operations and LTC tap changes.*

- **System Reactive Power Demand Index (SRPDI):** *average value of reactive power demands from the substation during the entire simulated period.*
- **System Energy Loss Index (SELI):** *the ratio of total energy loss and total load demand during the entire simulated period.*

Power Quality Scoring Methodology

◆ **Power Quality Score (PQS)**

Both min and max of each metric are calculated from the definition or determined from IEEE standards and practical limits.
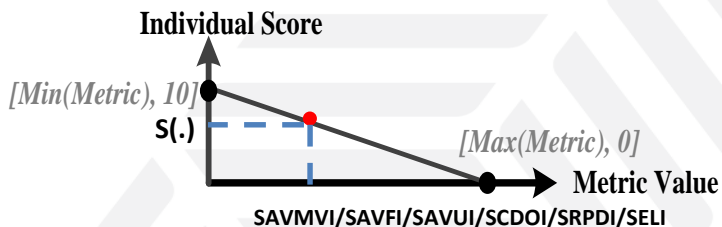
$$PQS = \alpha_{SAVMVI} \cdot S(SAVMVI) + \alpha_{SAVFI} \cdot S(SAVFI) + \alpha_{SAVUI} \cdot S(SAVUI)$$
$$\alpha_{SCDOI} \cdot S(SCDOI) + \ \alpha_{SRPDI} \cdot S(SRPDI) + \alpha_{SELI} \cdot S(SELI)$$

◆ **Case Study**

Model Property	Value
Substation Bank Size	45 MVA
Circuit Primary Voltage	21 kV
Number of Circuits	3
Peak Bank Load	37.09 MW
Max Circuit Distance	6.63 miles
Total Primary Circuit Miles	85.65 miles
Capacitor Banks	7 (12 MVAr total)

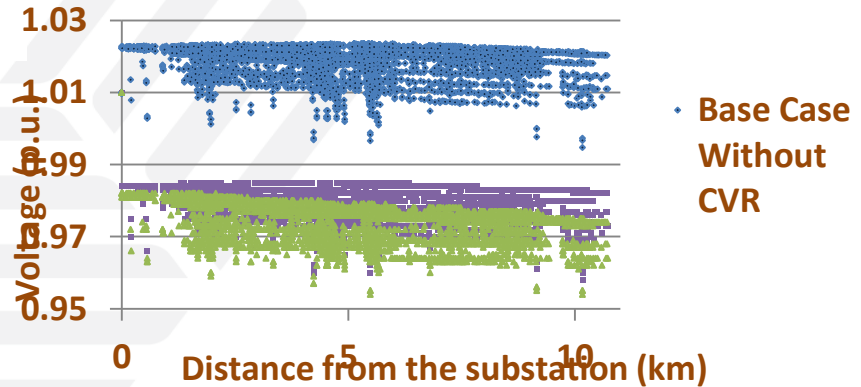| Scenario		
PV Penetration	0, 10%, 30%, 50%, 100% of peak load	
Smart Inverter Penetration	0, 25%, 50%, 100%	
Voltage Optimization	With, Without	
Simulation	1 year with 1 h time step	

One-Year Energy Saving
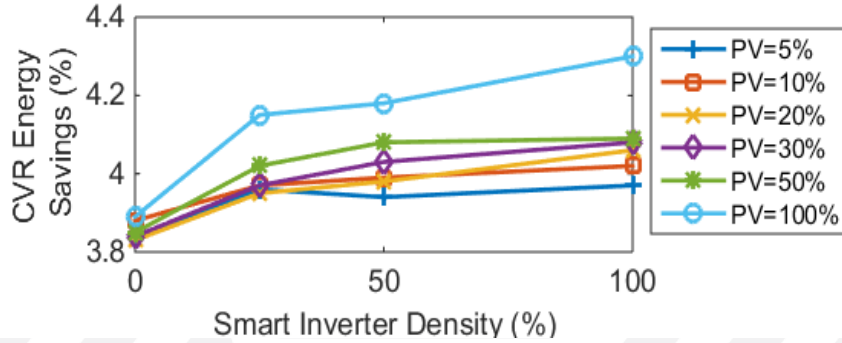
Voltage reduction energy savings at different PV penetrations and smart inverter densities.

Voltage profile at one time step obtained for three cases

Case Study 3: Conclusion

- Voltage reduction energy savings increased with autonomous smart inverter Volt-VAR control. Smart inverters with a lower VVC band center allowed the tap position of the substation LTC to be lower, compared to cases without smart inverters. This resulted in a lower distribution system voltage profile and increased voltage reduction energy savings.

- Since voltage reduction energy savings were prioritized over the PQS, the implementation of the proposed voltage reduction scheme lowered certain power quality scoring metrics, including SCDOI and SRPDI, leading to an overall lower PQS.

- Overall without CVR VO, smart inverters had a positive impact on the PQS, and helped to reduce energy losses and voltage fluctuations.