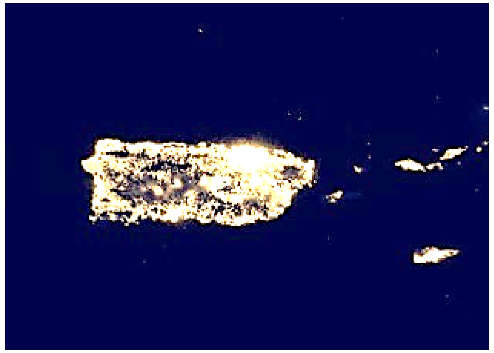
U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO)
Innovations in Distribution Grid Planning and Operations Webinar
June 24–25, 2021

Exceptional service in the national interest

Sandia National Laboratories






Voltage Regulation and Protection Assurance using Distributed Energy Resource Advanced Grid Functions

PRESENTED BY

Rachid Darbali-Zamora

Jay Johnson, Adam Summers, Clifford W. Hansen,
Javier Hernandez-Alvidrez and Matthew J. Reno

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

U.S. DEPARTMENT OF ENERGY

NNSA

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Introduction

With increasing interest in clean energy generation, interconnections with these renewable energy sources has become more common.

Distribution circuits with high penetrations of distributed energy may experience wide **voltage deviations** due to a variation in active power flows.

However, recent advancements in **grid-support functions**, PV inverters used to provide voltage regulation.

There has been research in **grid-support voltage regulation** techniques such as Fixed Power Factor (FPF), Optimal Power Factor (OPF), Volt-Var (VVC) functions as well as newer functions.

> *"These control approaches require further field testing with different physical systems to conclude their effectiveness and potential."*

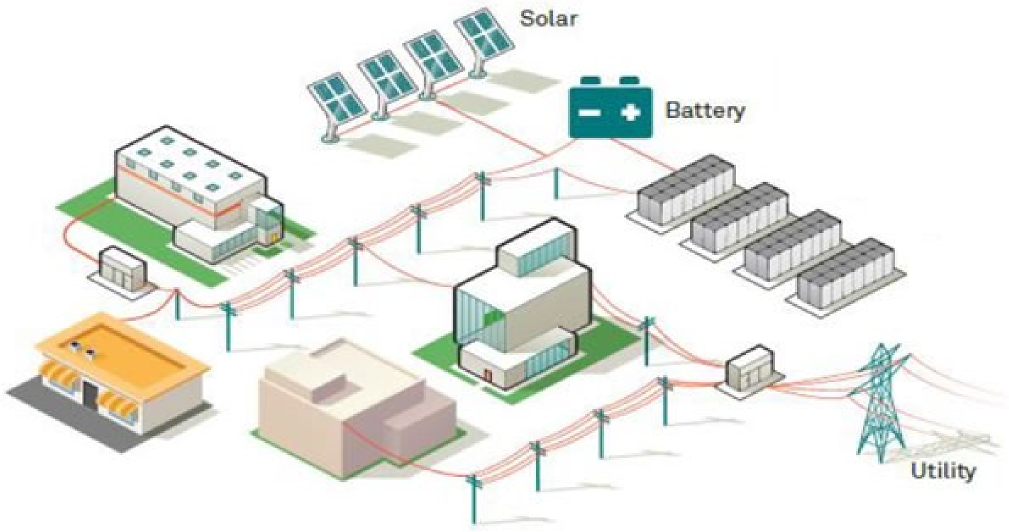


Fig. 1. Distribution System with Distributed Energy Sources.*

*www.bloomenergy.com/datasheets/microgrid-energy

Motivation

Power grids that incorporate a variety of distributed energy generation must be capable to maintaining **frequency** and **voltage** regulation in the allowable range against the disturbances caused by **load variations** and **variable generation** provided by renewable energy sources.

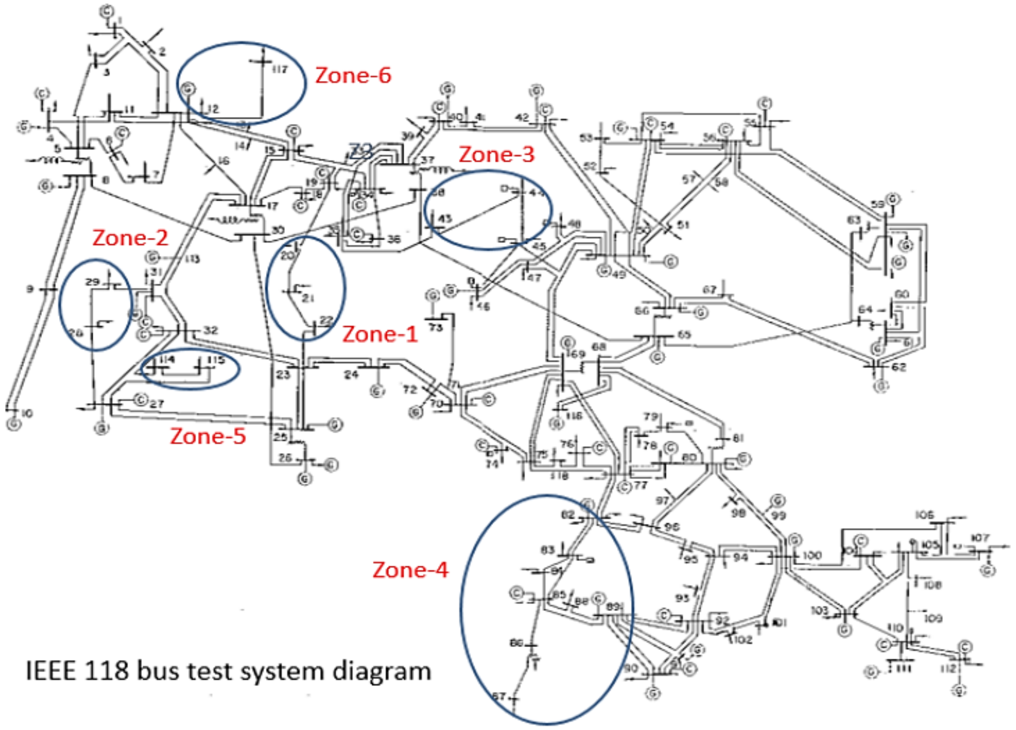


Fig. 2. IEEE 118 Bus test system.

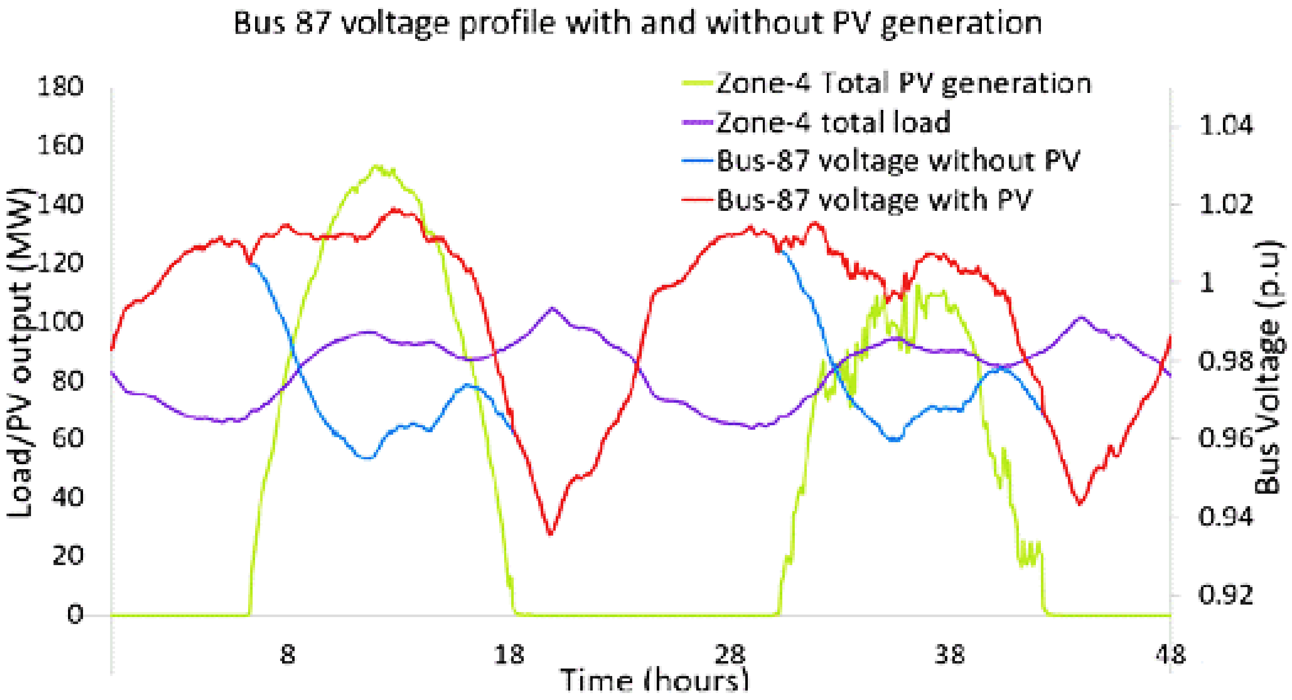


Fig. 3. Results from the IEEE 118 Bus test system.

*A Three-Stage Enhanced Reactive Power and Voltage Optimization Method for High Penetration of Solar

Problem Formulation

Context

- Total installed capacity of PV is growing fast.
- Moreover, large growth of PV is expected in distribution systems.

Problem

- Grid is slow to evolve, we encounter technical challenges with voltage/frequency regulation, protection, etc.
- Unless we tackle this issue, these challenges will make it increasingly difficult and costly to continue integrating renewable energy or limit PV growth.

Hypothesis

- We can improve the technology integrated into the system by employing several grid support functionality.
- Depending on the capacity of the system, location and communications capabilities, one of these voltage regulation methods will perform better than the others.

Research Questions

- What are advantages and disadvantages of Volt-Var Curve (VVC), Extremum Seeking Control (ESC) and Particle Swarm Optimization (PSO)?
- How can the methods be evaluated with physical devices prior to field implementation?

Objectives

The main objective is to determine the best **method for voltage regulation by identifying the advantages and disadvantages of FPF, VVCs and ESC** on an actual PV inverter connected to a power distribution system with other PV inverters.

Objective 1. Establish and validate a bench mark **RT-PHIL platform.**

Deliverable: *Develop distribution feeder to understand challenges in PHIL, Including: feeder calibration. sample size, device selection, lead compensator.*

Objective 2. Perform **RT-PHIL experiments with simulated and hardware PV Inverter**.

Deliverable: *Develop and validate PV inverter models.*

Objective 3. Develop and validate **distribution feeder** models based on reduced existing PNM and NG models.

Deliverable: *Develop and validate distribution feeder models based on realistic systems to accurately capture challenges of a realistic feeder (loads, LTC, PV).*

Objective 4. Implement three voltage regulation grid-support functions.

Deliverable: *Systematic study of the effects of VVC, ESC and PSO as well as a proof of concept into implementing a RT-PHIL approach before field deployment.*

Proof of Concept

Voltage Regulation Power Simulations

↓

Real-Time Voltage Regulation Power Simulations

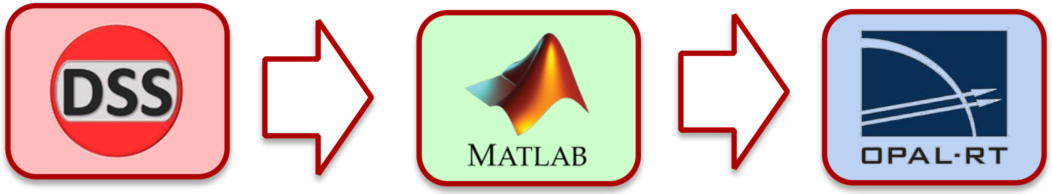
↓

Power Hardware-in-the-Loop Voltage Regulation Power Simulations

↓

Field Demonstrations on Live Power Systems

Methodology



What is Real-Time Power Hardware-in-the-Loop?

Real-Time (RT) simulation provides the ability to solve computational models in **RT**.

Power Hardware-in-the-Loop (PHIL) enables dynamic power behavior of physical devices to be represented in large power simulations.

The combination of **RT** simulation and **PHIL** interfaces hardware into a simulation environment to study.

This allows for an **affordable and reliable alternative** to testing physical devices under real operating conditions before they are connected to an actual system.[1]

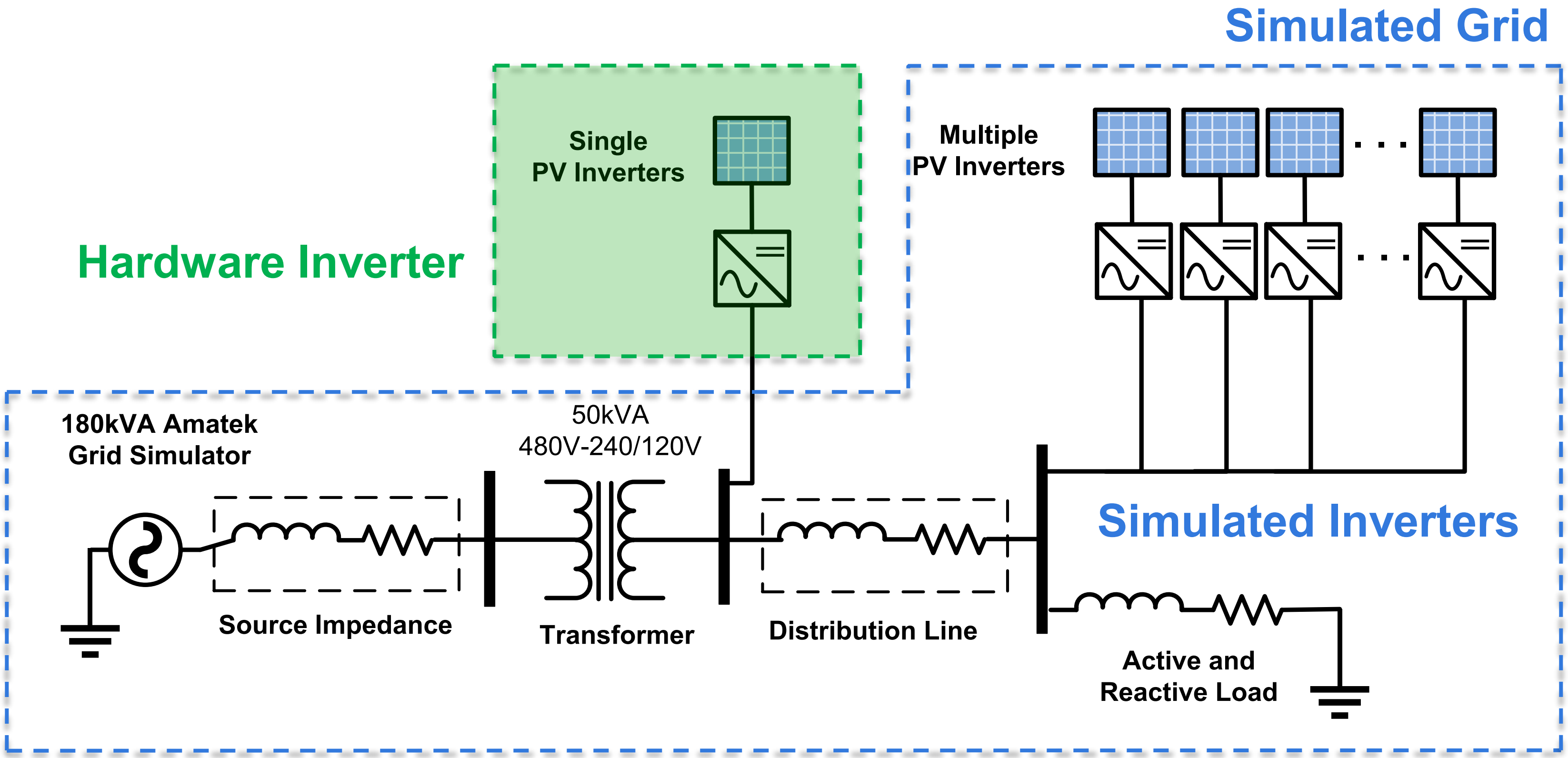


Fig. 4. Example of a Distribution Simulation System with Hardware and Emulated PV

[1]R. Darbali, J. Hernandez, A. Summers; ***"Fault Validation Utilizing a Real-Time Power Hardware-in-the-Loop Approach for Rural Distribution Feeders with Photovoltaic Systems"***; 2019 Photovoltaic Specialist Conference.

Implementing Real-Time Power Hardware-in-the-Loop Platform

MATLAB/Simulink can be used to build power systems simulations models that can be executed in **RT**.

Opal-RT is able to input and output analog signals from these power system models.

Power amplifiers can be used to scale these signals and emulate an electrical grid.

This allows hardware components to be connected to the simulated electrical grid, completing the **PHIL**.

This approach is known as the *Ideal Transformer Method (ITM)*.[1]

[1]A. Summers, J. Hernandez, R. Darbali; ***"Comparison Between the Ideal Transformer Method and the Damping Impedance Method for RT PHIL"***; 2019 Photovoltaic Specialist Conference.

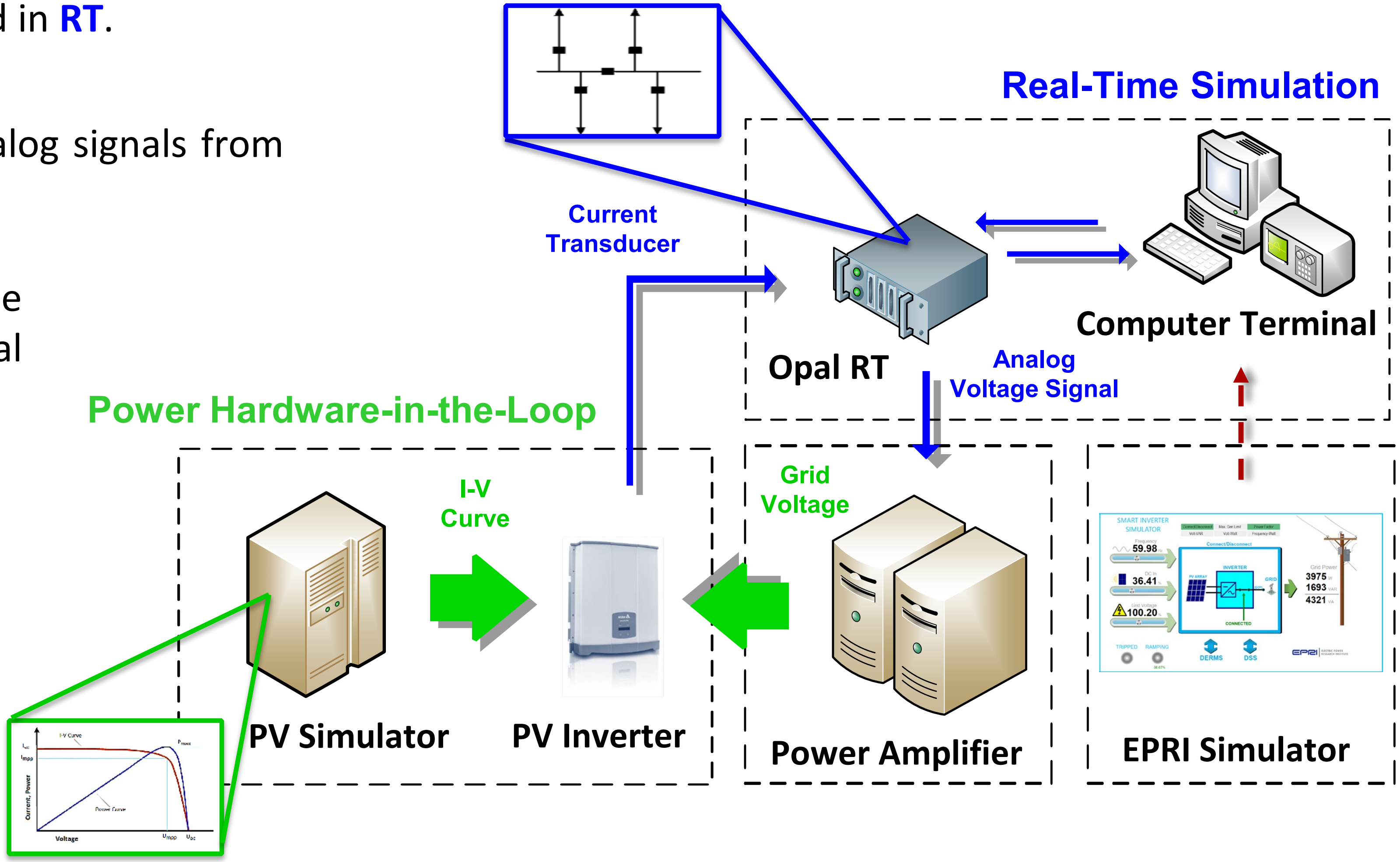


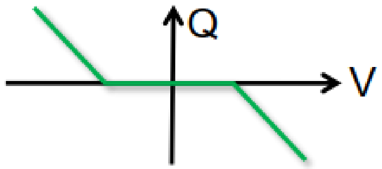
Fig. 5. Setup for the DETL OPAL-RT Platform for PV Inverter Testing.

Voltage Regulation Approaches

This project proposes a performance comparison between FPF, VVC and ESC. Moreover, this project identifies which situations should one voltage control technique should be used over the other.

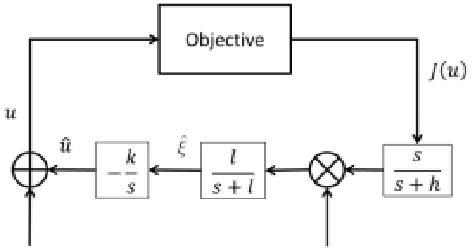
Volt-Var Curve (VVC)

- Function: Volt-VAR



Extremum Seeking Control (ESC)[1]

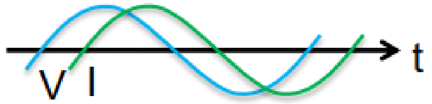
- Function: New Grid-Support Function



Particle Swarm Optimization (PSO)

- Function: Power Factor or Reactive Power Commands

Note: Forecasting PV generation.
State estimating load behavior.[2]



[1]J. Johnson et al., **"Distribution Voltage Regulation Using Extremum Seeking Control With Power Hardware-in-the-Loop,"** in IEEE Journal of Photovoltaics, vol. 8, no. 6, pp. 1824-1832, Nov. 2018.

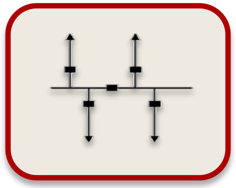
[2]J. Johnson, et al., "**Optimal Distribution System Voltage Regulation using State Estimation and DER Grid-Support Functions**," Sandia Technical Report, SAND2020-2331, Feb 2020.

Creating Realistic Power Simulation Models

SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

Sandia National Laboratories

- Feeder models, based on existing distribution systems were reduced to smaller equivalent distribution systems using the **OpenDSS.**[1]
- These models were migrated into **MATLAB/Simulink** and simulated in RT with a simulated PV inverter.[2]
- The **OPAL-RT** platform was used to demonstrate the capabilities of **RT- PHIL.**



DSS

MATLAB

OPAL-RT

Collect information on distribution system.

Reduce model and simulate distribution system in **OpenDSS**.

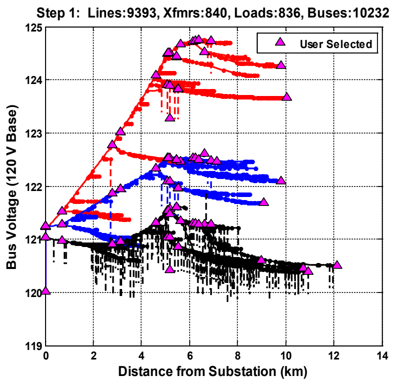
Obtain **RT** simulation in **MATLAB/Simulink** on the **OPAL-RT**.

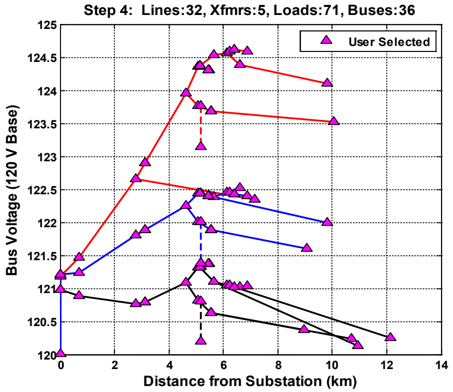
Obtain **RT-PHIL** experimental results in **MATLAB/Simulink** on the **OPAL-RT**.

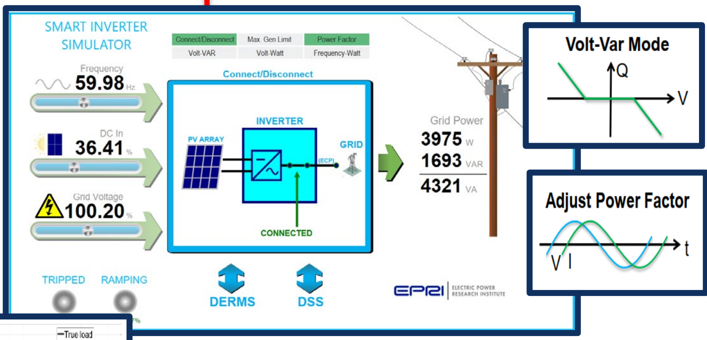
Before Reduction			
Line	Xfmr	Load	Bus
9393	840	836	10232

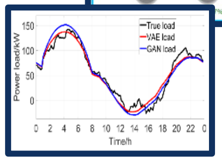
After Reduction			
Line	Xfmr	Load	Bus
32	5	71	36

Simulated PV systems were used in the RT and RT-PHIL simulations.









EPRI Simulator

[1]M. J. Reno, *et al.*, "**Reduction of distribution feeders for simplified PV impact studies**," *2013 IEEE 39th Photovoltaic Specialists Conference*, pp. 2337-2342.

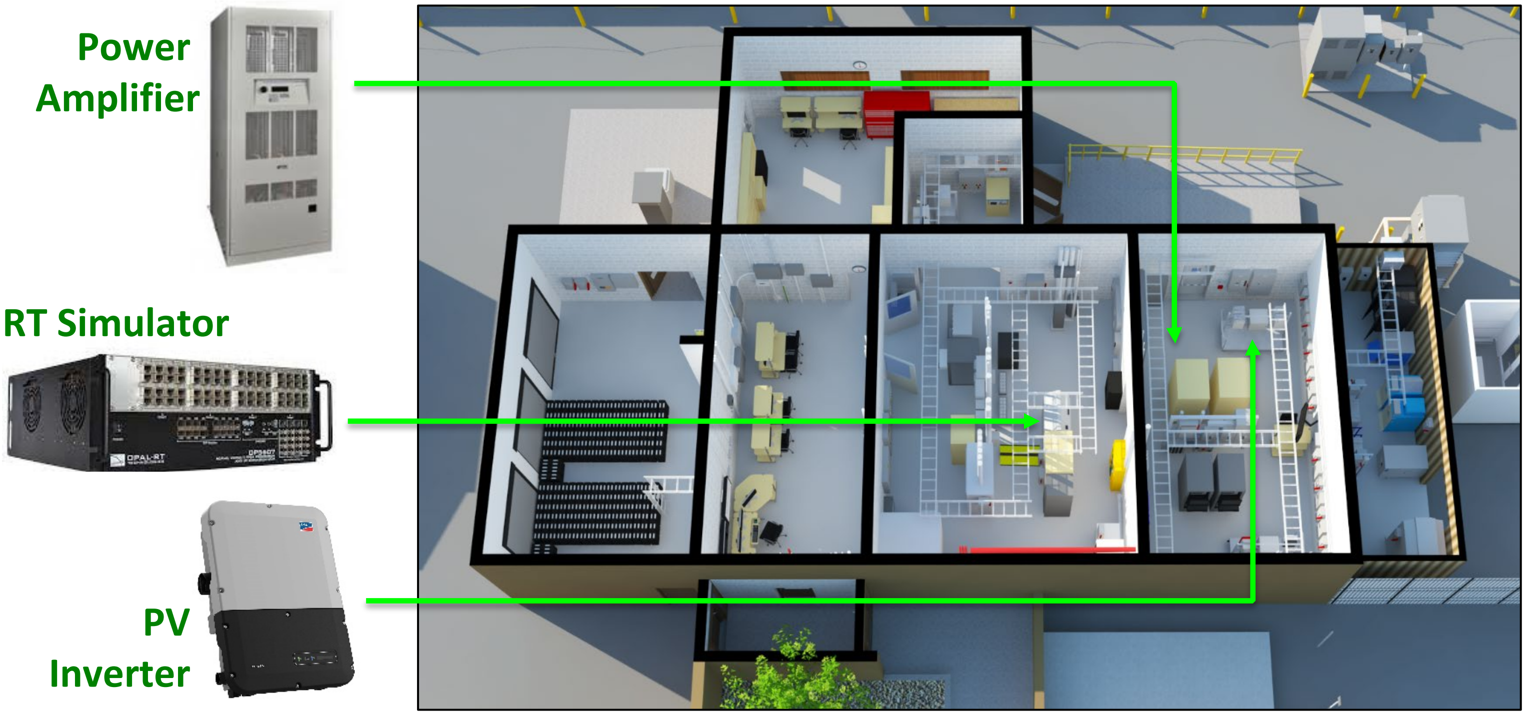
[2]R. Darbali-Zamora, *et al.*, "***Validation of a Real-Time Power Hardware-in-the-Loop Distribution Circuit Simulations with Renewable Energy Sources***", *IEEE 7th World Conference on Photovoltaic Energy Conference (WCPEC)*, Waikoloa, Hawaii, June 10-15, 2018.

Distributed Energy Technology Laboratory at Sandia National Laboratories

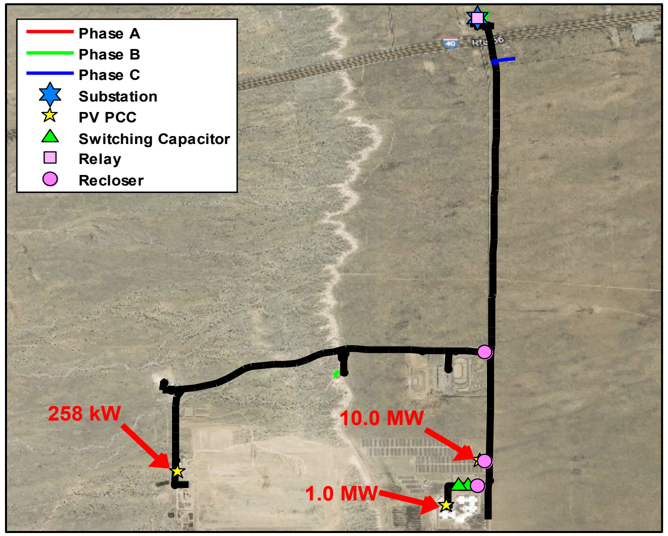
- The **Distributed Energy Technologies Laboratory (DETL)**, located at Sandia National Laboratories in Albuquerque, NM, and provides **unique** power systems and power electronics testing capabilities.

- The laboratory also has an OPAL-RT real-time simulator used to perform RT-PHIL tests with single phase or three phase PV inverters.

- DETL researchers have extensive expertise in **DER grid-integration**.



Test Case A:
Public Service Company of New Mexico (PNM) Distribution Feeder Model



Test Case A: Creating the PNM Distribution Feeder Model

The system consists of **three PV inverters** with nameplate capacities of 1 MVA, 10 MVA and 258 kVA for a total PV production of **11,258 kVA**.

Notice that the PNM is a relatively balanced system.

Table I: Reduction Process

Before Circuit Reduction Process				After Circuit Reduction Process			
Lines	Xfmrs	Loads	Buses	Lines	Xfmrs	Loads	Buses
196	20	20	217	12	2	14	15

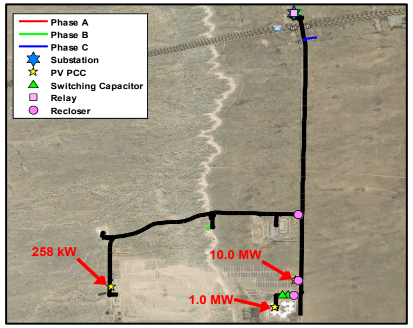


Table II: Summary of Load Data

Phase	Active (kW)	Reactive (kVar)
A	841	471
B	852	472
C	875	476
Total	**2,569**	**1,419**

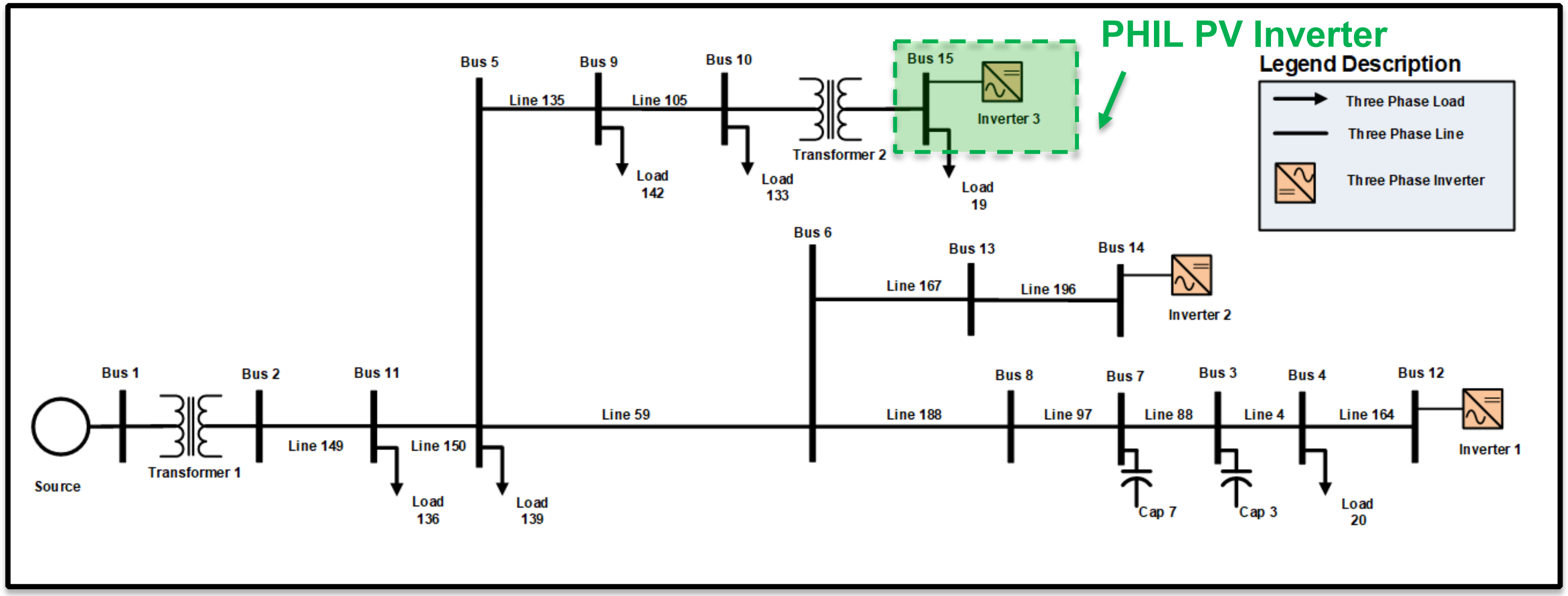
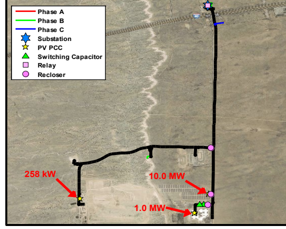


Figure 6. The PNM Three-Phase Distribution System.



Test Case A: PNM Distribution Feeder Real-Time Simulation

The active power of the different voltage regulation approaches overlaps.

This means there is enough headroom that active power curtailment does not occur.Oscillations in the ESC are due to the parameter selection for the probing signal.

There is no load connected at the bus where PV inverters 2 is located, which makes its reactive power absorption consistent.

Baseline	No Control
VVC	Volt-Var Curve
ESC	Extremum Seeking Control
PSO	Particle Swarm Optimization

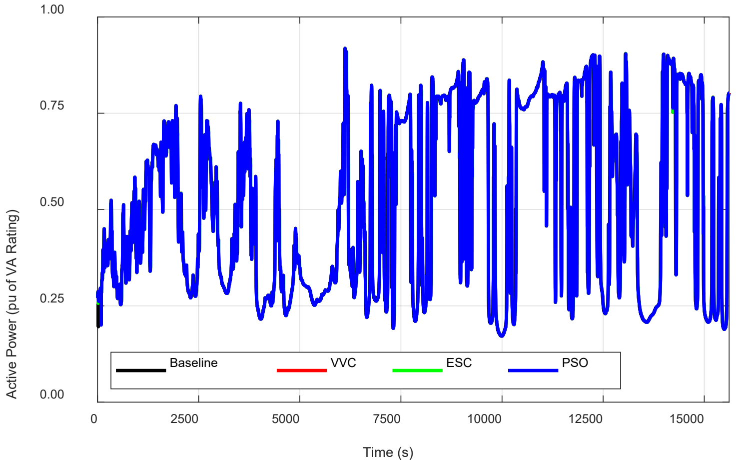


Fig. 7. Simulated Active Power for PV 1.

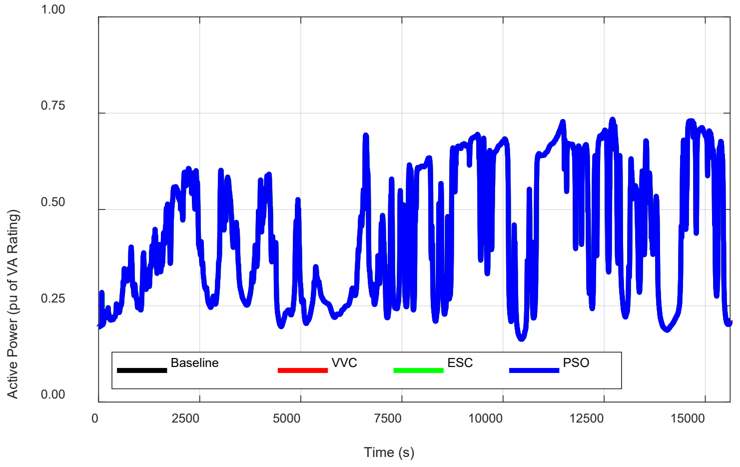


Fig. 8. Simulated Active Power for PV 2.

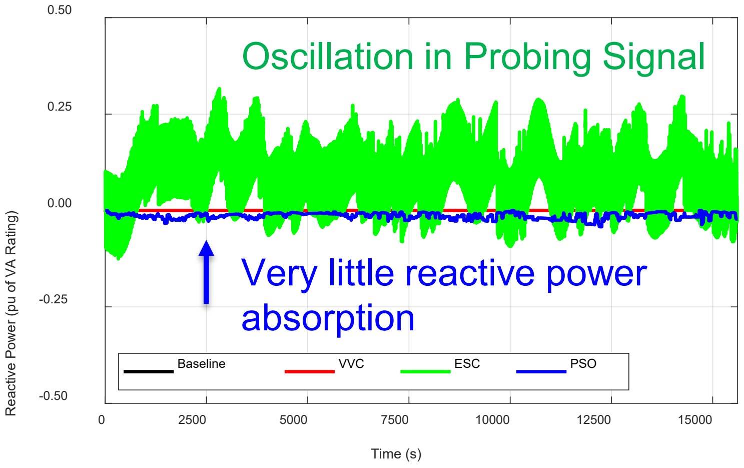


Fig. 9. Simulated Reactive Power for PV 1.

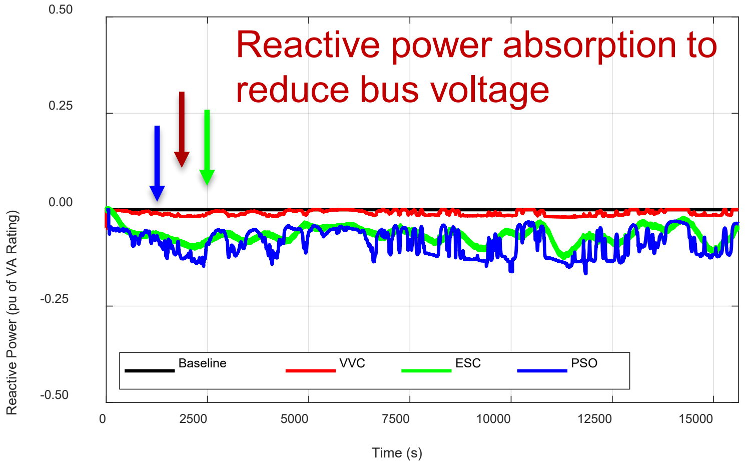
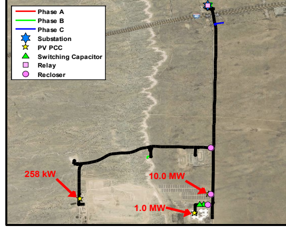


Fig. 10. Simulated Reactive Power for PV 2.



Test Case A: Simulated Results for the PNM Model

ESC and PSO improve voltage regulation at the PCC of PV inverter 1.

- The average bus voltage is close to nominal (Good).
- The maximum voltage is reduced substantially (Good).
- The minimum voltage is reduced (Bad).

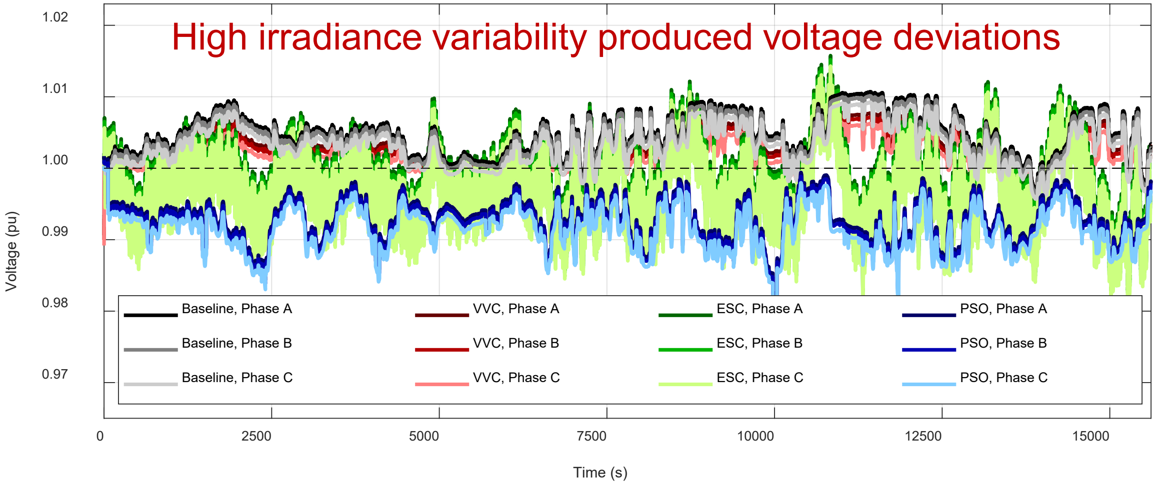


Fig. 11. Voltage at PV inverter 1 PCC .

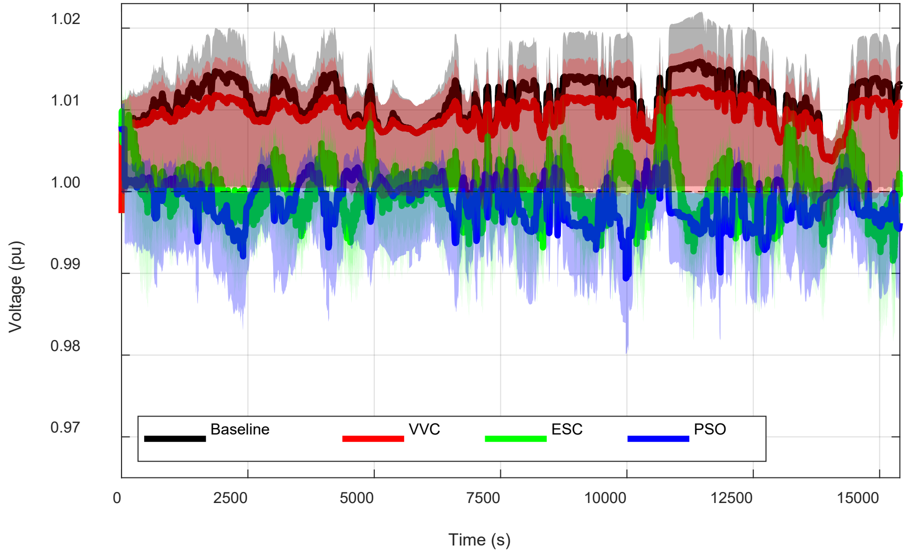
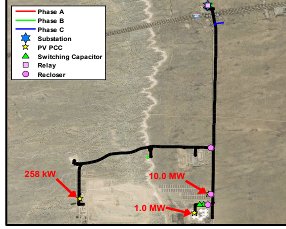


Fig. 12. Comparison of Voltage Regulation.

Baseline	No Control
VVC	Volt-Var Curve
ESC	Extremum Seeking Control
PSO	Particle Swarm Optimization

Test Case A: PNM Power Hardware-in-the-Loop Experiment



For the experimental results using a **PHIL** PV inverter, results are obtained between baseline and PSO (VVC and ESC are not evaluated).

Notice that at the PCC of the **PHIL** PV inverter, the voltage is lower than nominal.

The PSO grid support function control attempts to regulate the overall system voltage to the desired target voltage.

Notice from the experimental results that the PSO approach is able to reduce the maximum and minimum voltage band.

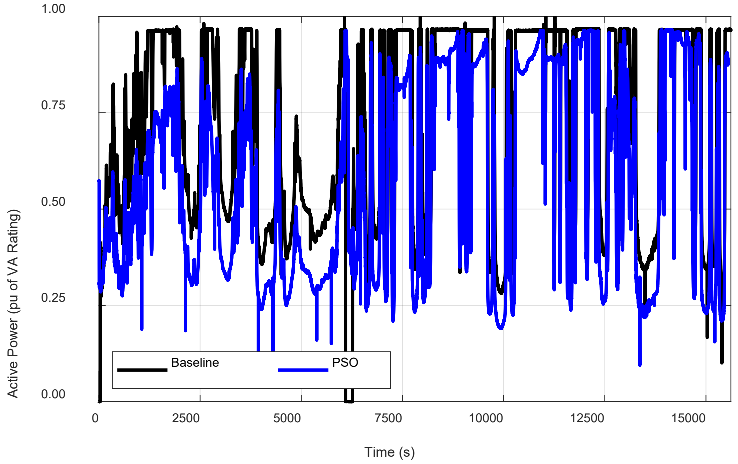


Fig. 13. Active Power of PV inverter 1.

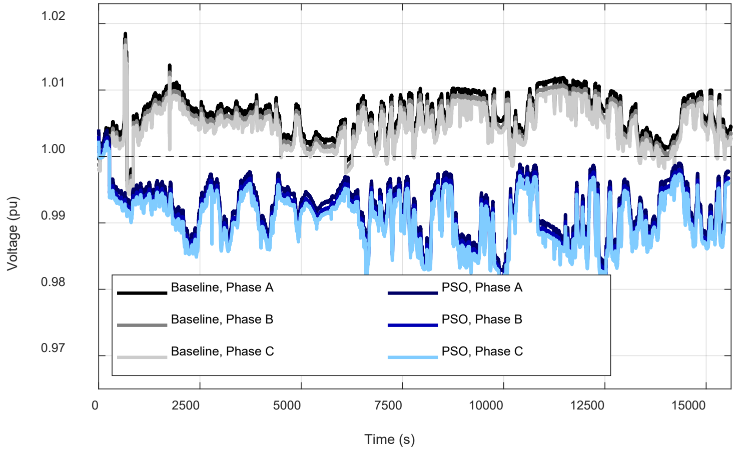


Fig. 14. Voltage at PV inverter 1 PCC .

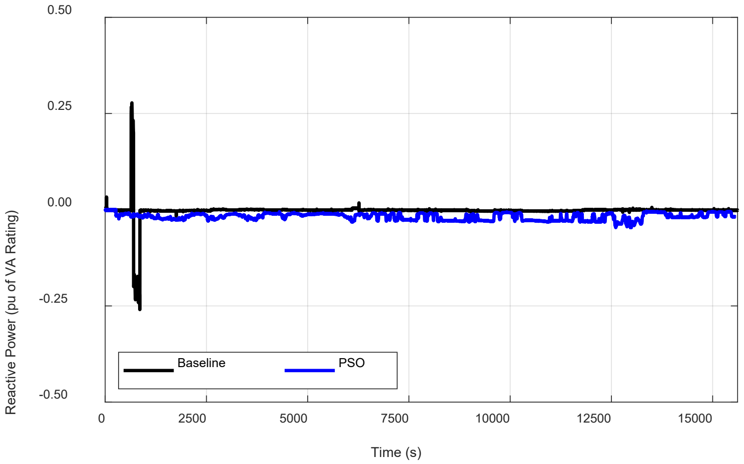


Fig. 15. Reactive Power PV inverter 1.

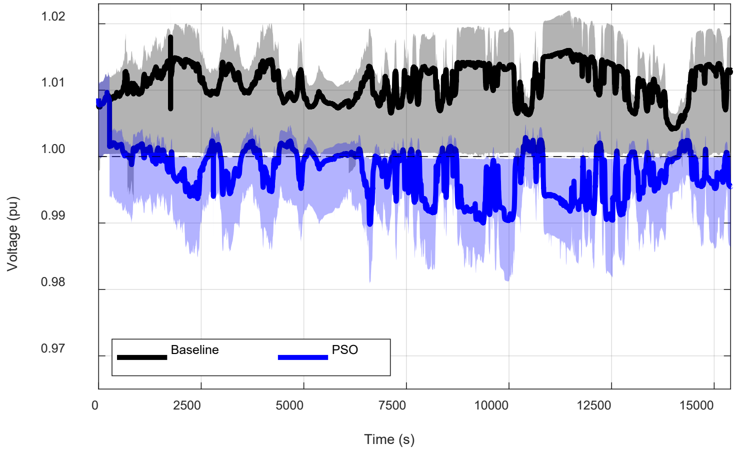
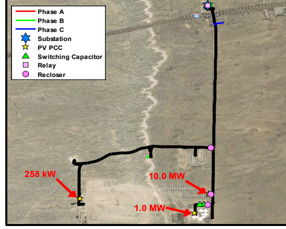


Fig. 16. Comparison of Voltage Regulation.

What are some lessons learned from ESC and PSO?



Different selection of the ESC parameters can yield a response with more oscillations.

The reactive power **probing signal's** impact on the feeder voltage is clearly seen in the results.

It was found that absolute care must be taken to use the same component and settings for the Simulink/RT-Lab and OpenDSS models; otherwise erroneous solutions will be found.

Binary variables (e.g., capacitor banks) and discrete variables must have consisted behavior between the OpenDSS time-series simulation and Simulink/RT-Lab model.

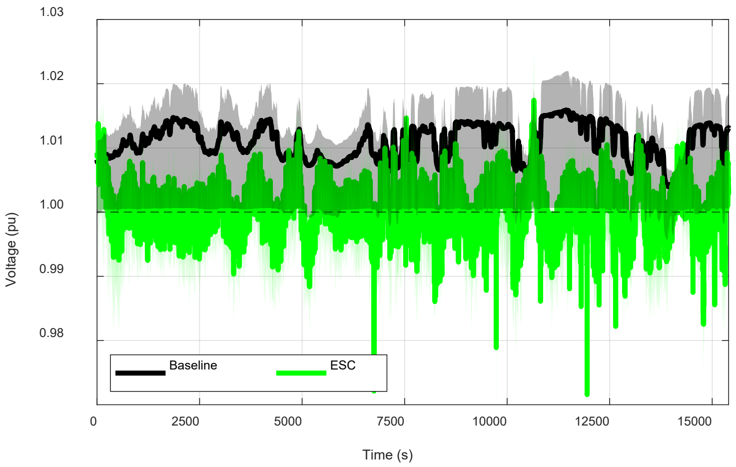


Fig. 17. ESC with Excessive Oscillation.

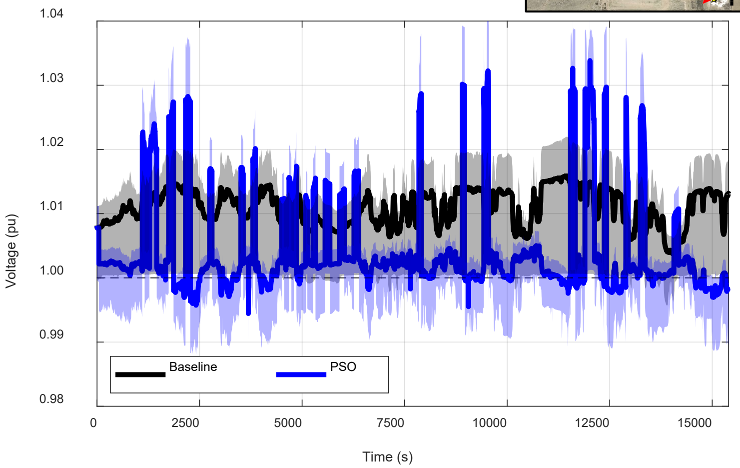


Fig. 18. PSO with Inconsistent Capacitor Switching.

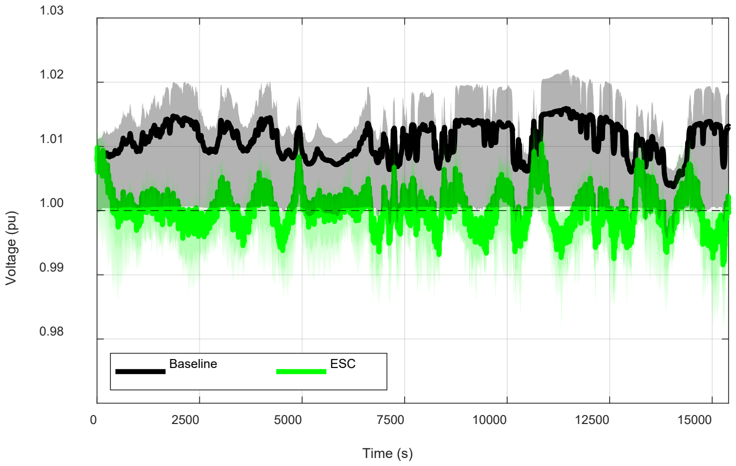


Fig. 19. ESC with Reduced Oscillation.

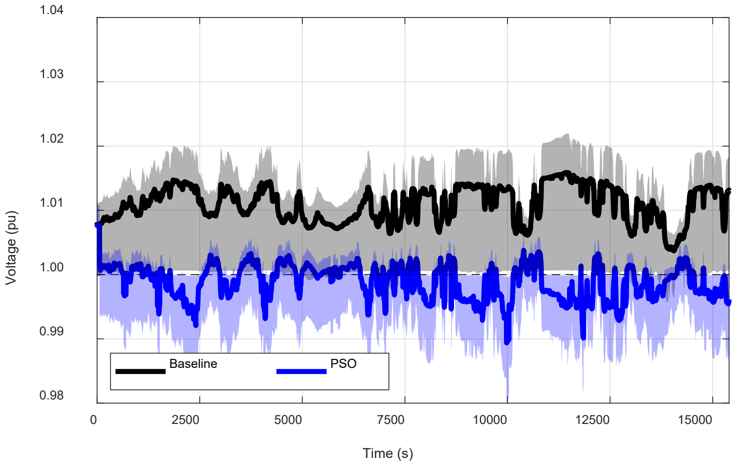
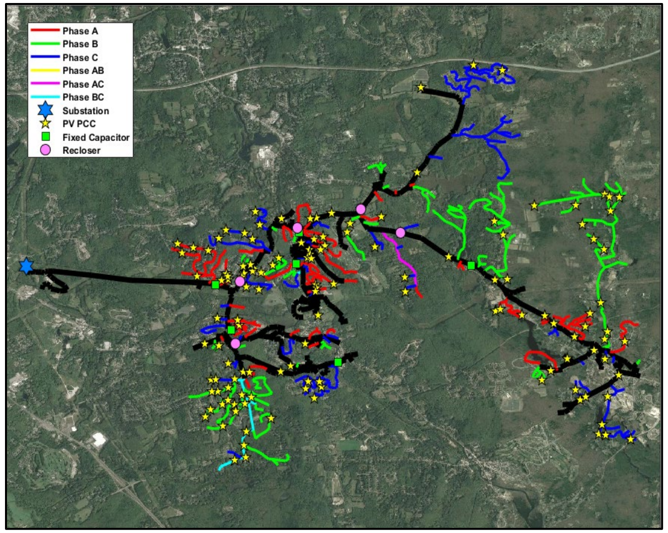


Fig. 20. PSO with no Capacitor Switching.

Test Case B:
National Grid (NG) Distribution Feeder Model

nationalgrid



Test Case B: Creating the NG Distribution Feeder Model

The system consists of one **three PV inverter and 30 single phase PV inverters,** with a total PV production of **6,179 kVA**.

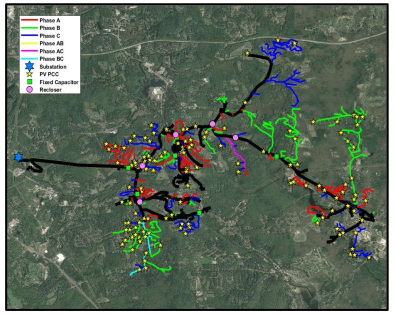


Table VI: Summary of Load Data

Phase	Active (kW)	Reactive (kVar)
A	3,232	1,514
B	3,037	1,839
C	3,232	2,004
Total	**9,501**	**5,357**

Loads are unbalanced

Table III: Reduction Process

Before Circuit Reduction Process				After Circuit Reduction Process			
Lines	Xfmrs	Loads	Buses	Lines	Xfmrs	Loads	Buses
1,579	4	656	1,582	13	3	43	15

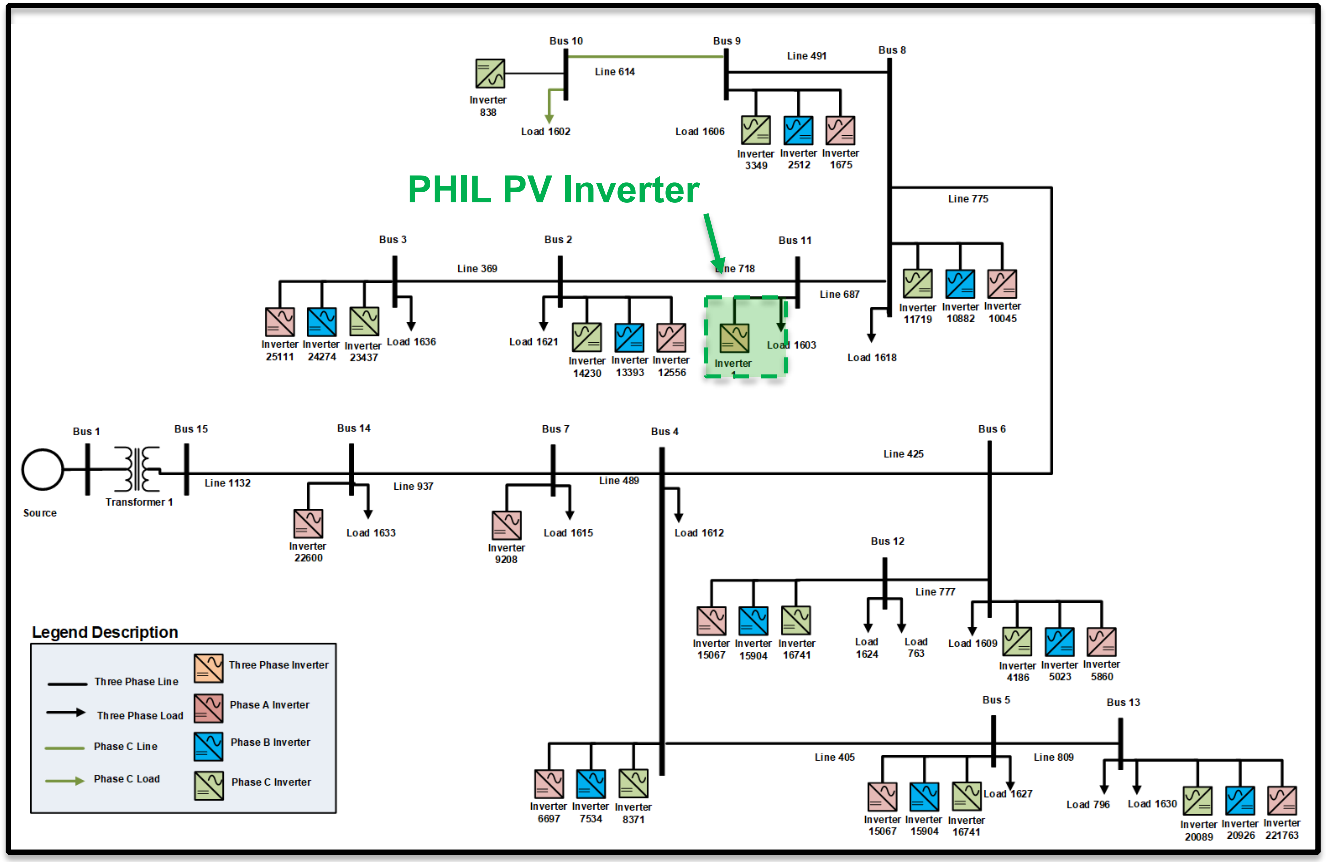
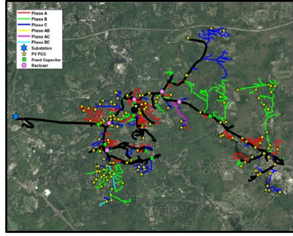


Fig. 21. The NG Three-Phase Distribution System.

Test Case B: NG Distribution Feeder Real-Time Simulation



For the NG model, **only one PV inverter is controlled.** All other PV inverters are operating at MPPT (they are not providing reactive power for voltage regulation).

Notice that VVC does not show significant reactive power generation, while PSO and ESC demonstrate larger reactive power values.

Phases are above 1 pu for the first half of the simulation and then below 1 pu for remaining time.

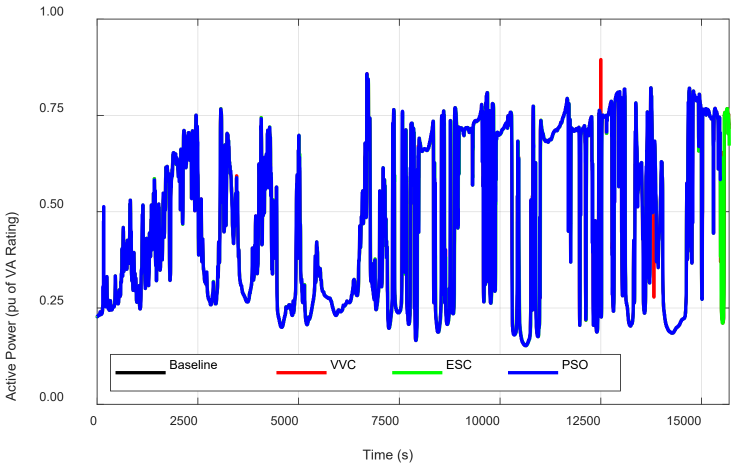


Fig. 22. Simulated Active Power for PV 9208.

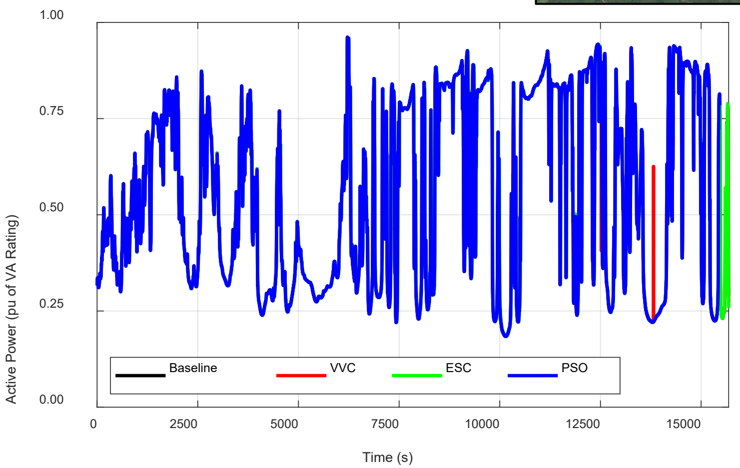


Fig. 23. Simulated Active Power for PV 1.

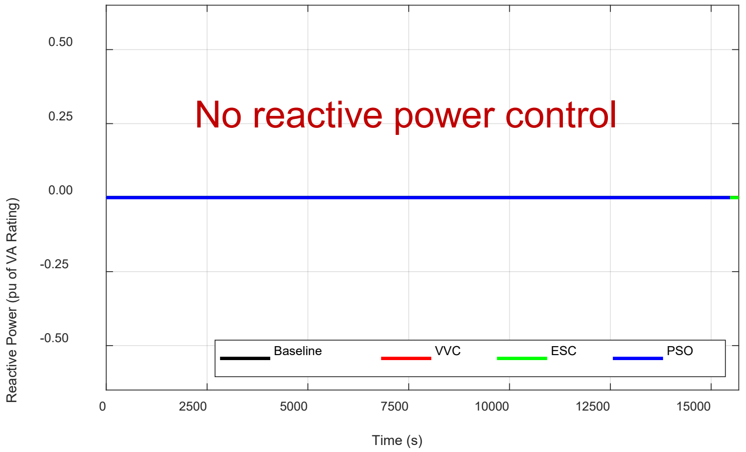


Fig. 24. Simulated Reactive Power for PV 9208.

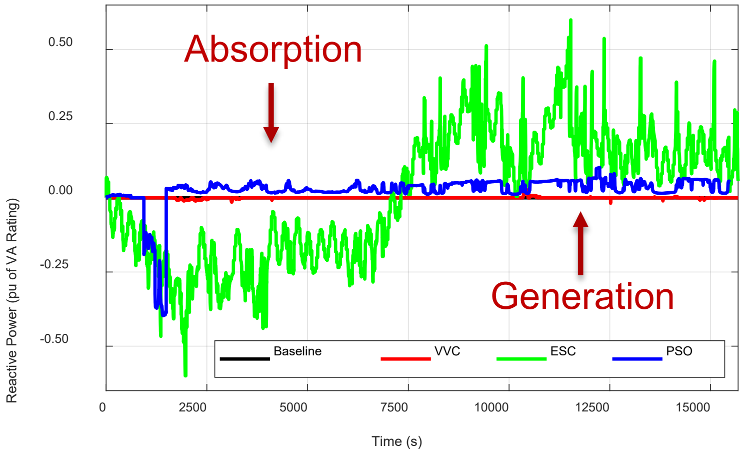
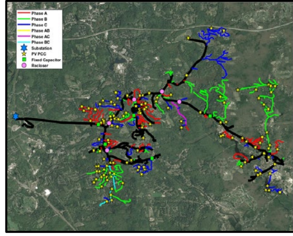


Fig. 25. Simulated Reactive Power for PV 1.

Test Case B: Simulated Results for the NG Model



Notice that the NG system was highly unbalanced.

None of the voltage regulation techniques were capable of correcting the voltage deviations using the 3 phase PV inverters at Old Upton Road.

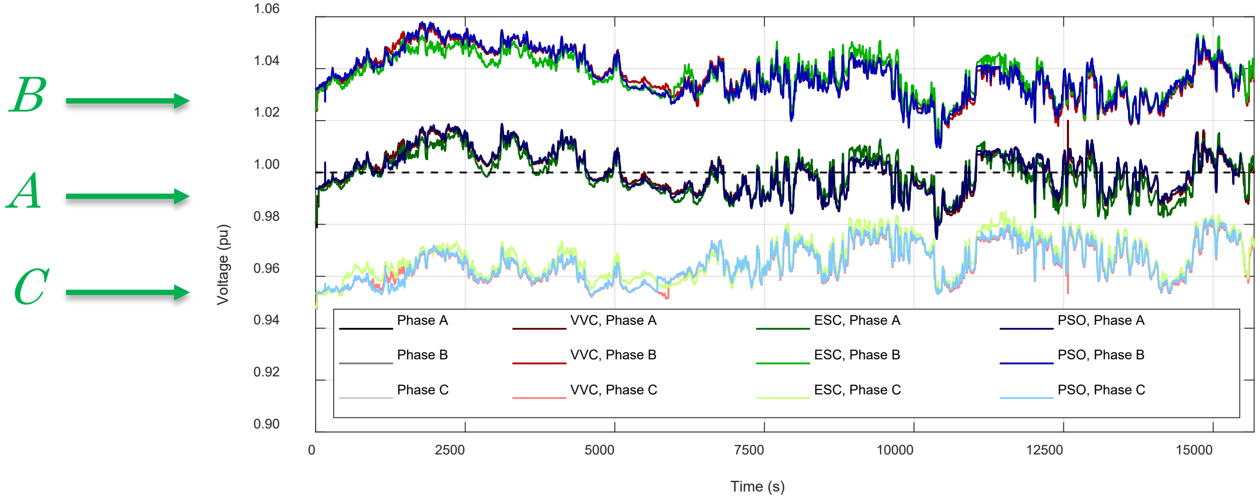


Fig. 26. Voltage at PV inverter 1 PCC .

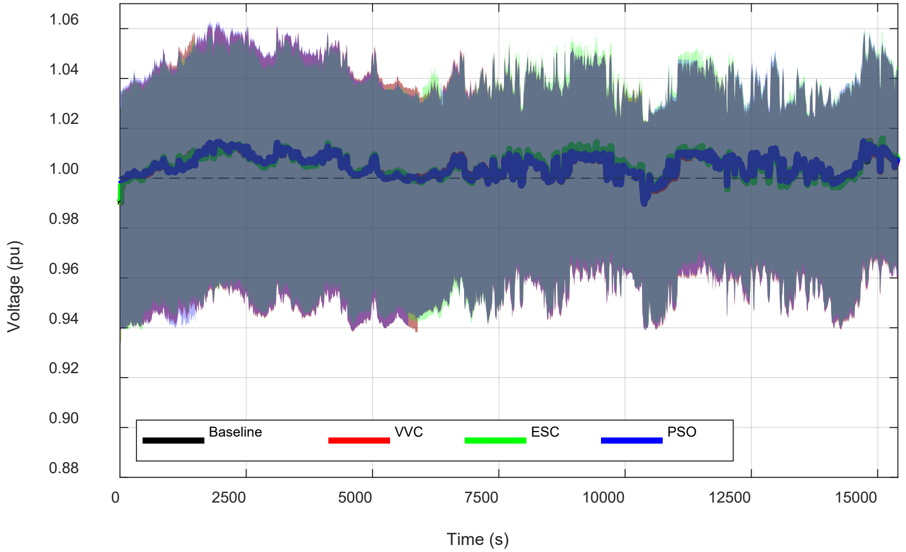
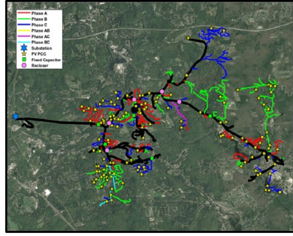


Fig. 27. Comparison of Voltage Regulation.

Baseline	No Control
VVC	Volt-Var Curve
ESC	Extremum Seeking Control
PSO	Particle Swarm Optimization

Test Case B: NG Power Hardware-in-the-Loop Experiment



For the experimental results using a **PHIL** PV inverter, results are obtained between baseline and PSO (VVC and ESC are not evaluated).

The experimental **PHIL** results reinforce the observations in the simulation results.

The three phase PV inverter system located in Old Upton Road cannot correct phase unbalance.

Question: *If control of all the single phase PV inverters were employed, (not just Old Upton Road) would there be improvement in phase unbalance?*

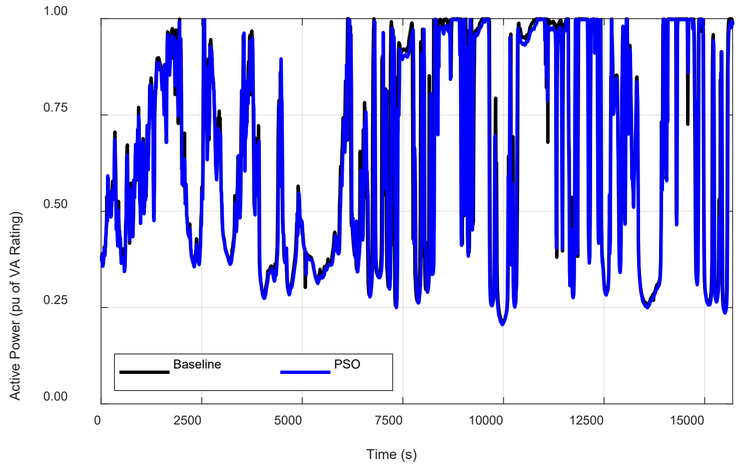


Fig. 28. Baseline Active Power Profiles.

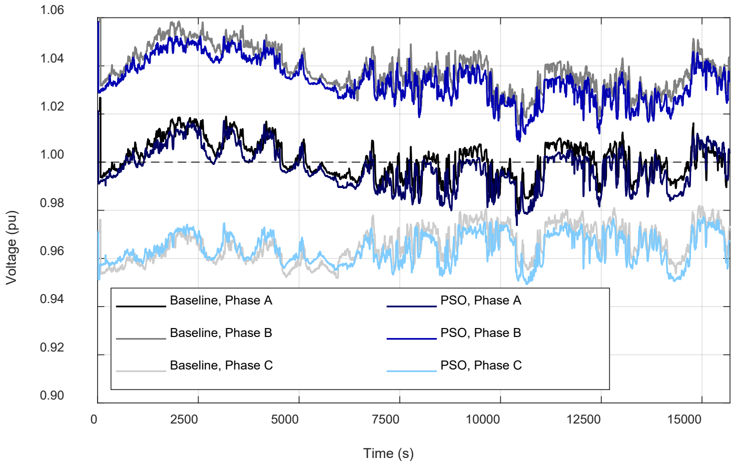


Fig. 29. Voltage at PV inverter 1 PCC .

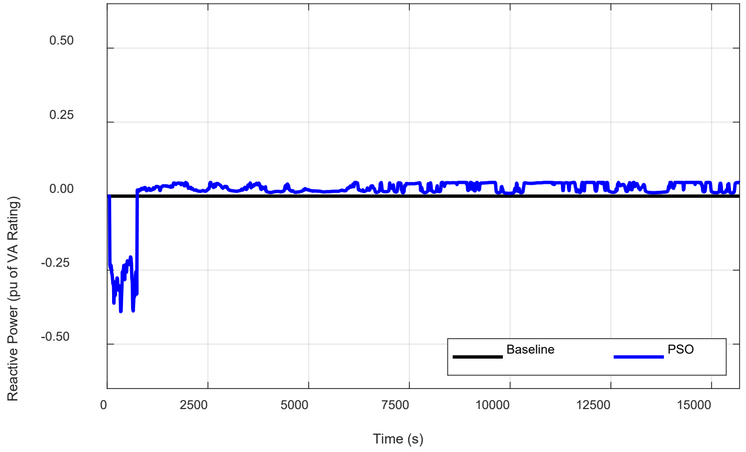


Fig. 30. Baseline Reactive Power Profiles.

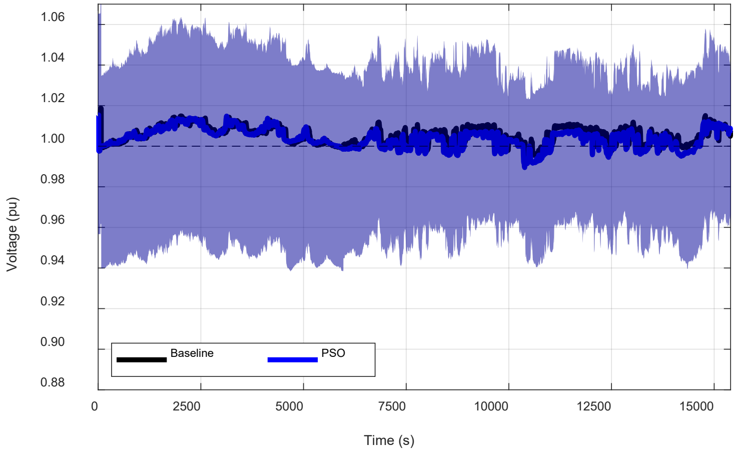
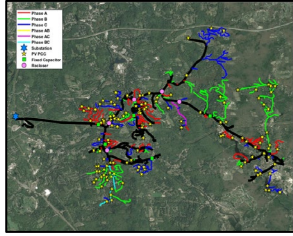


Fig. 31. Comparison of Voltage Regulation.

What if we could control all the PV inverters?



For this case, all PV inverters are programmed to provide reactive power generation/absorption for voltage regulation.

PV inverter 1 is a three phase PV inverter that attempts to correct the average phase bus voltage evenly.

PV inverter 9208 is a single phase PV inverter. The reactive power absorption for the is due to its attempt to reduce voltage in phase A.

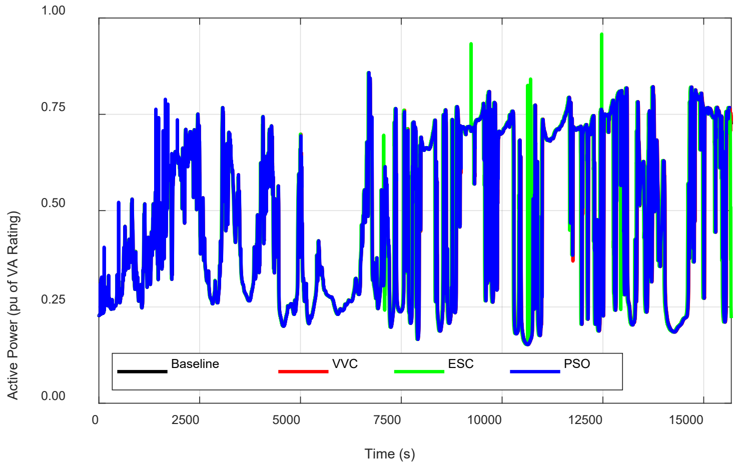


Fig. 32. Simulated Active Power for PV 9208.

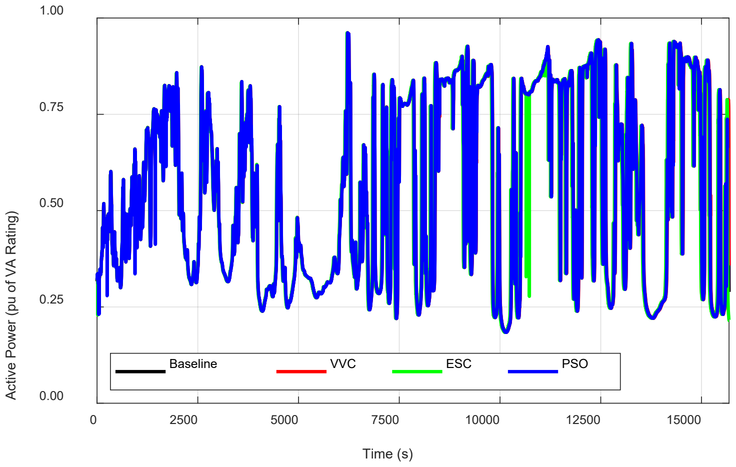


Fig. 33. Simulated Active Power for PV 1.

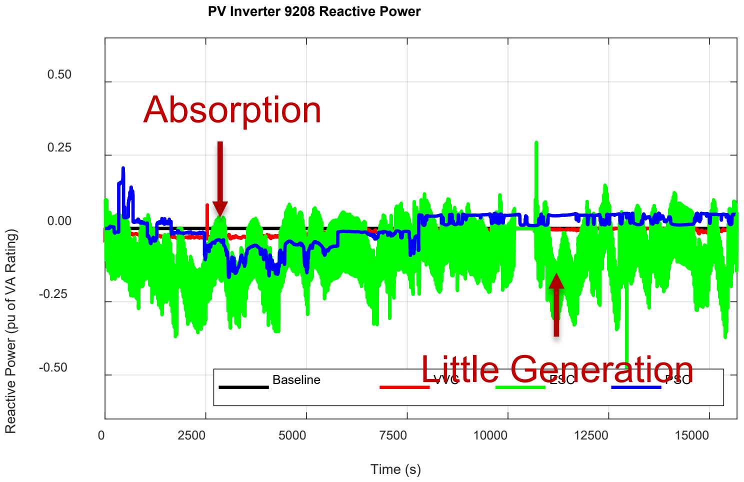


Fig. 34. Simulated Reactive Power for PV 9208.

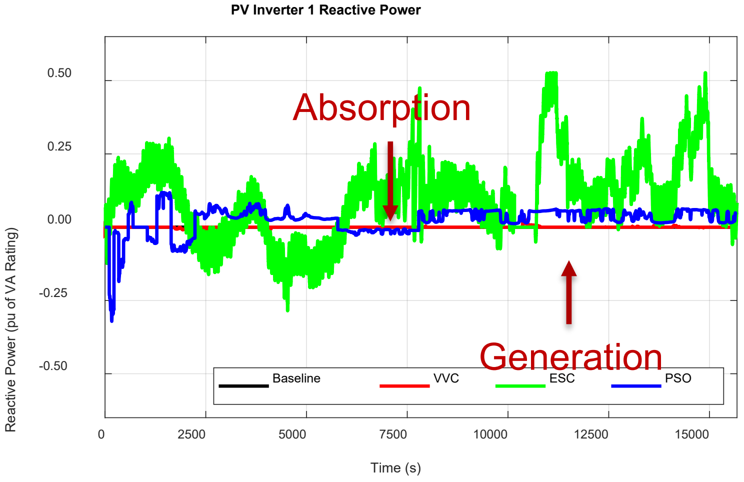
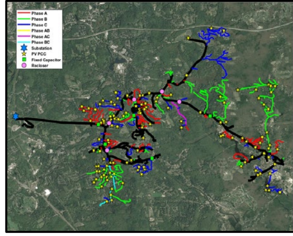


Fig. 35. Simulated Reactive Power for PV 1.

Controlling a single PV inverter Vs. Controlling all of them



For these and all other grid support functions; size, location, and rating of the PV inverters is important.

A comparison of a distribution system where only one PV inverter is controlled where all PV inverters have grid support function capabilities.

Baseline	No Control
VVC	Volt-Var Curve
ESC	Extremum Seeking Control
PSO	Particle Swarm Optimization

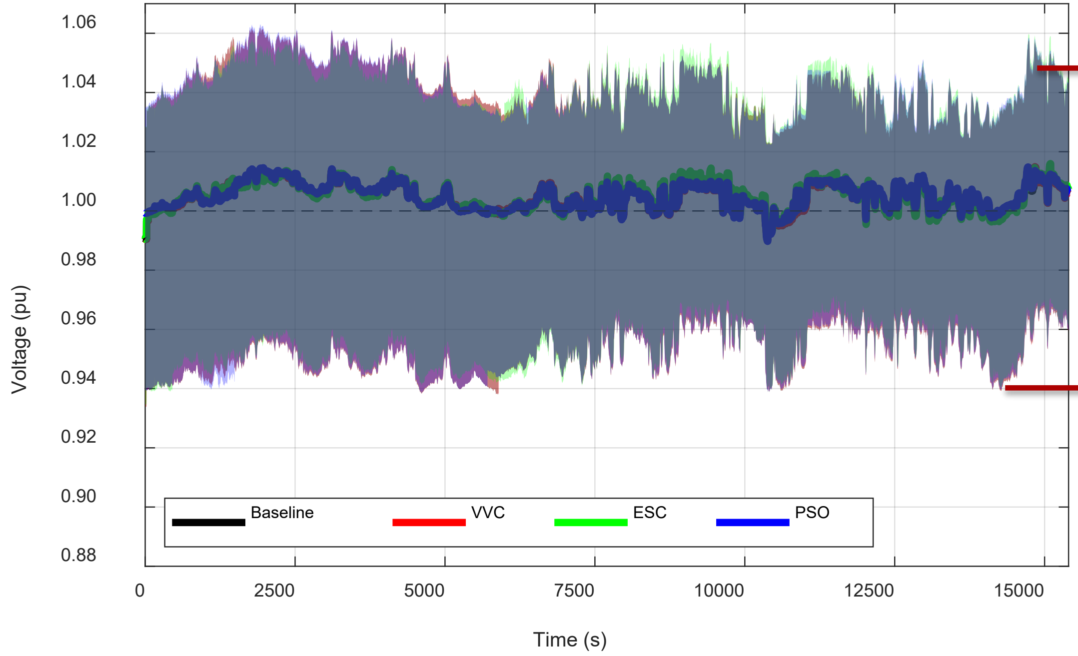


Fig. 36. Comparison of Voltage Regulation Controlling a single PV.

Reduced

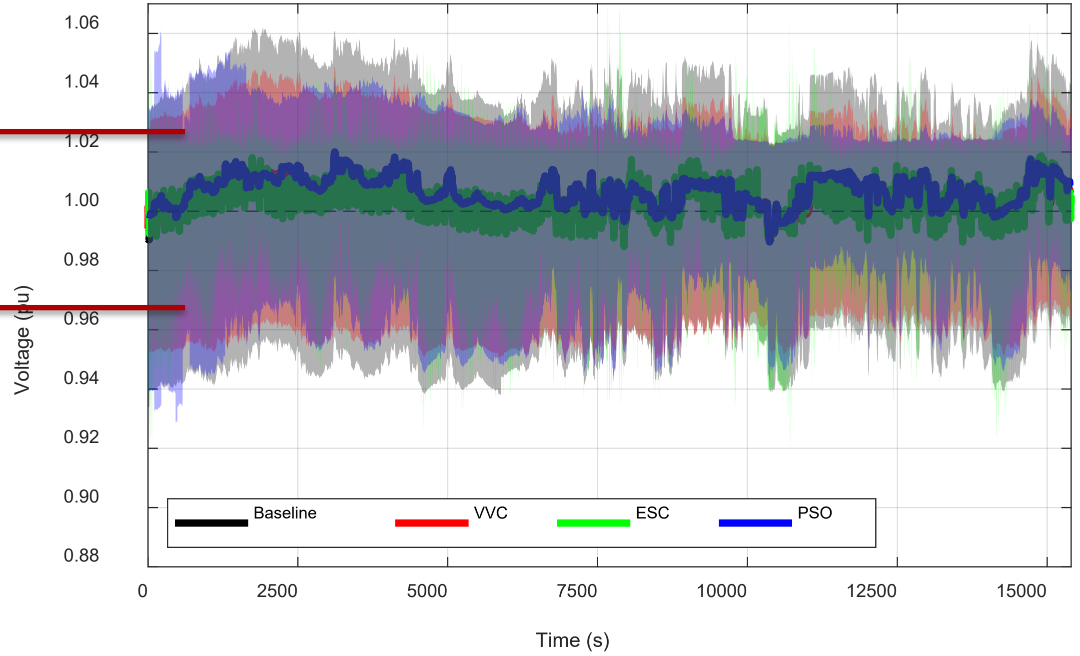
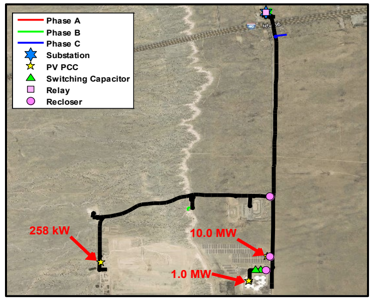
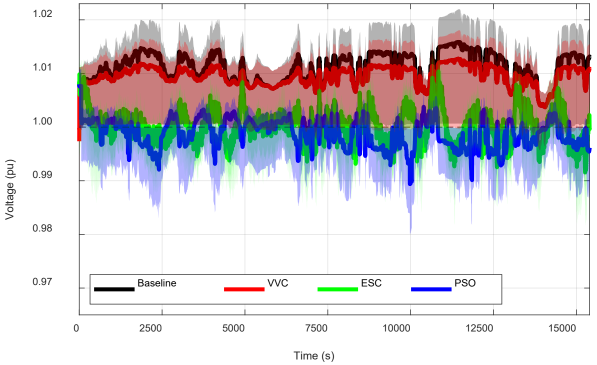


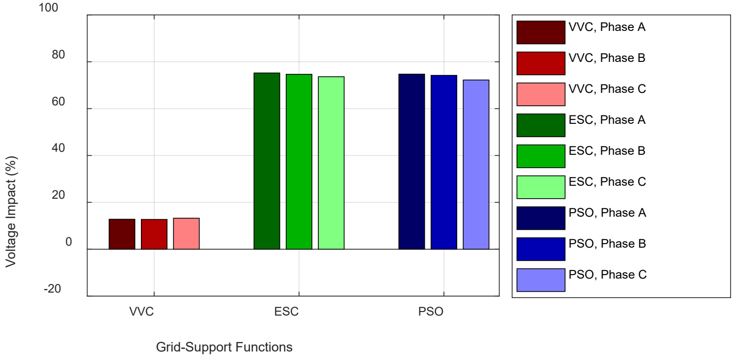
Fig. 37. Comparison of Voltage Regulation Controlling Multiple PV.

Summary of Real-Time Simulation Results[1]

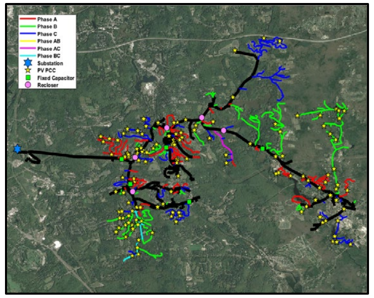
PNM controlling all PV inverters.

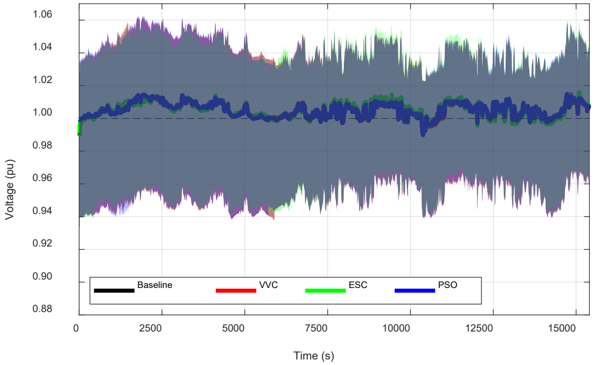


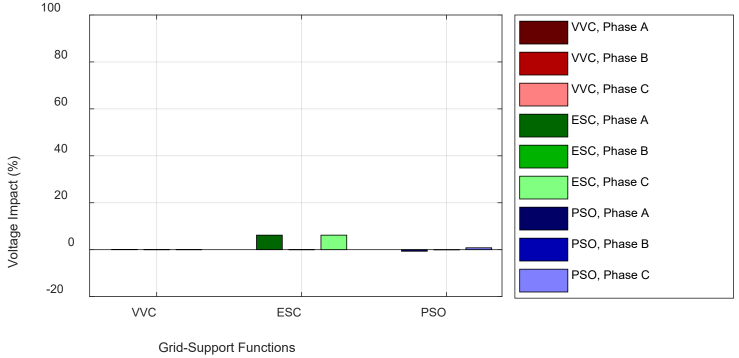




NG controlling a single PV inverter site.

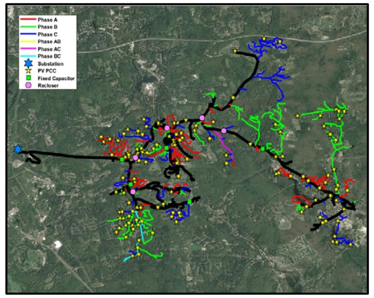


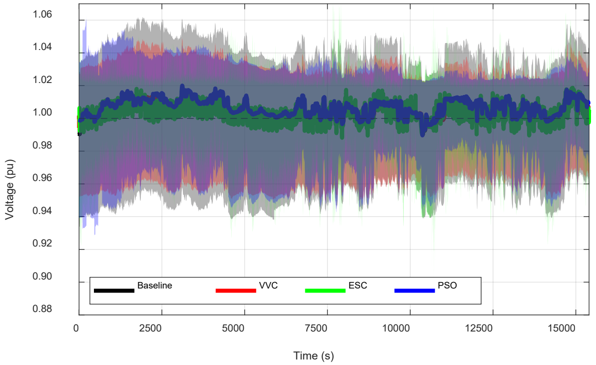


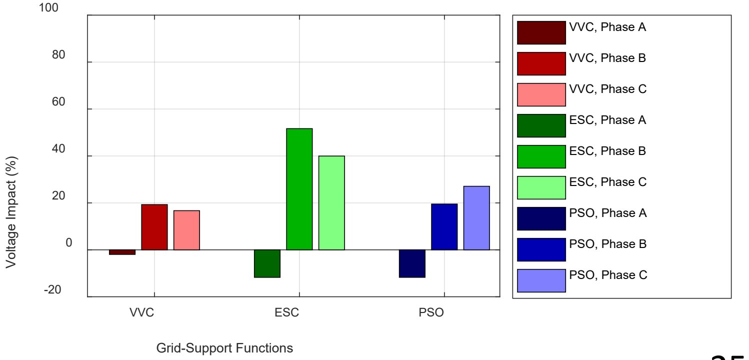


NG Controlling all PV inverters.

Baseline	No Control
VVC	Volt-Var Curve
ESC	Extremum Seeking Control
PSO	Particle Swarm Optimization

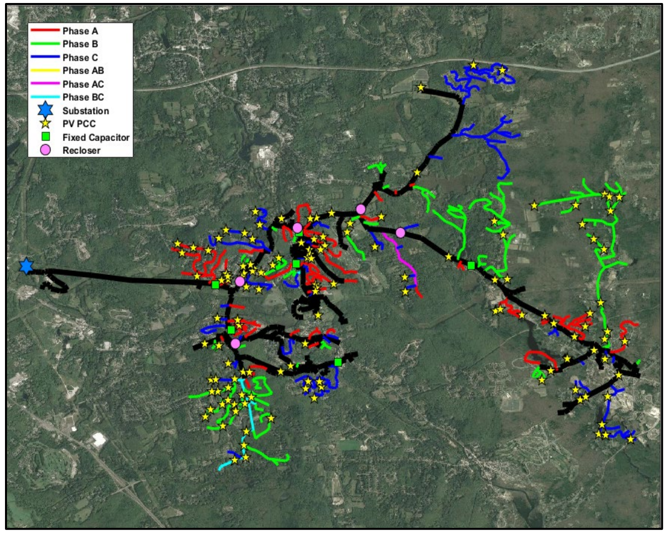






[1]A. Summers, J. Johnson, R. Darbali-Zamora, C. Hansen, J. Anandan, C. Showalter; **"A Comparison of DER Voltage Regulation Technologies using Real-Time Simulations"**, MDPI-Energies, Special Issue: Advancements in Real-Time Simulation of Power and Energy Systems, May 18, 2020.

Field Demonstration
National Grid (NG) Distribution Circuit Feeder



Implementing the Field Demonstration in the NG Site

The team ran VVC, ESC, and PSO OPF control techniques on the live NG feeder in Grafton, Massachusetts.

- 28 Three Phase PV inverters were controlled at the 672 kVA PV site.
- A feeder monitor located at a separate location on the feeder was be used to collect feeder voltages.
- Data was collected for multiple days for each control technique to compare the techniques.
- Connected Energy executed the simulation.

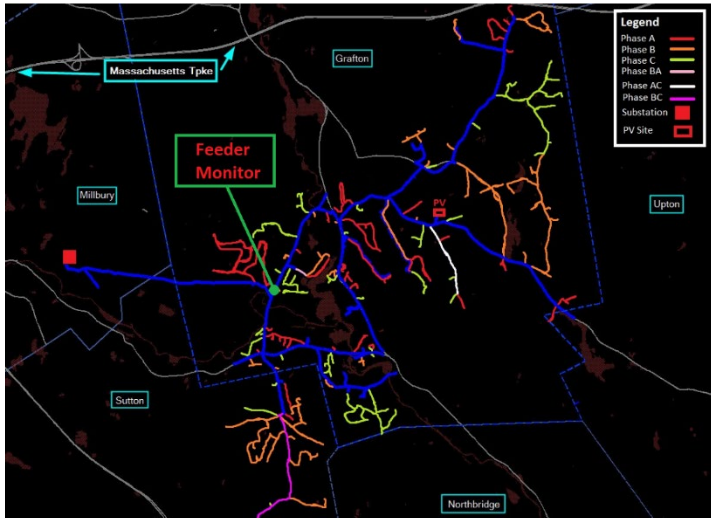


Fig. 38. NG Field Demonstration Location in Massachusetts.

Digital Twin Concept

RT state estimation using a **digital twin** can overcome the lack of in-field measurements inside an electric feeder to optimize grid services provided by DERs.

Georgia Tech developed dynamic state estimation used for the **digital twin** and protection portions of the project. GT comparted state estimation data to live power measurements.

A new technology called the Programmable Distribution Resource Open Management Optimization System (ProDROMOS) issued optimized DER reactive power setpoints based-on results from a particle swarm optimization (PSO) algorithm wrapped around OpenDSS time-series feeder simulations.[1]

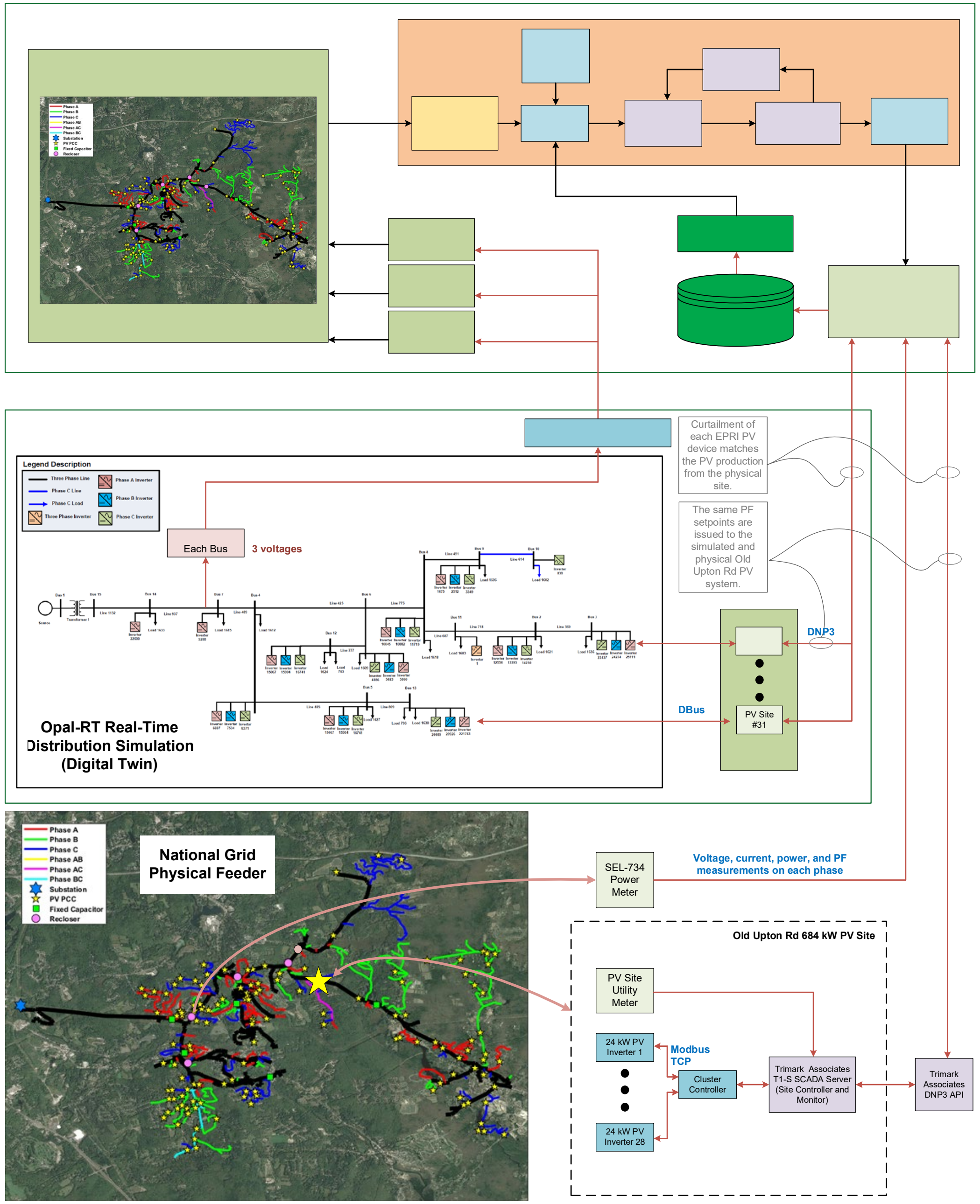


Fig. 39. Digital Twin Concept.

[1]J. Johnson, R. Darbali-Zamora, A. Summers and C. Hansen; U.S. Non-Provisional Patent; **"Digital Twin Advanced Distribution Management System (ADMS) and Methods"**, filed on March 6, 2020.

Results from the Digital Twin Platform

The RT digital twin effectively provides state estimation pseudo-measurements that can be used to optimize DER operations for distribution voltage regulation.[1]

These results demonstrate that the developed PHIL platform for the NG distribution feeder provides an adequate representation of the distribution system in the field.

Overall, the PSO operated near unity and could do little to help the voltage imbalance of the distribution feeder.

[1]R. Darbali-Zamora, J. Johnson, A. Summers, C. Birk Jones, C. Hansen, C. Showalter; **"State Estimation-Based DER Optimization for Distribution Voltage Regulation in Telemetry-Sparse Environment using a Real-Time Digital Twin",** MDPI-Energies, Special Issue: Distributed Power Generation: Energy Sources, Control, Energy Management and Power Electronics, pp 1-20, Jan 19, 2021.

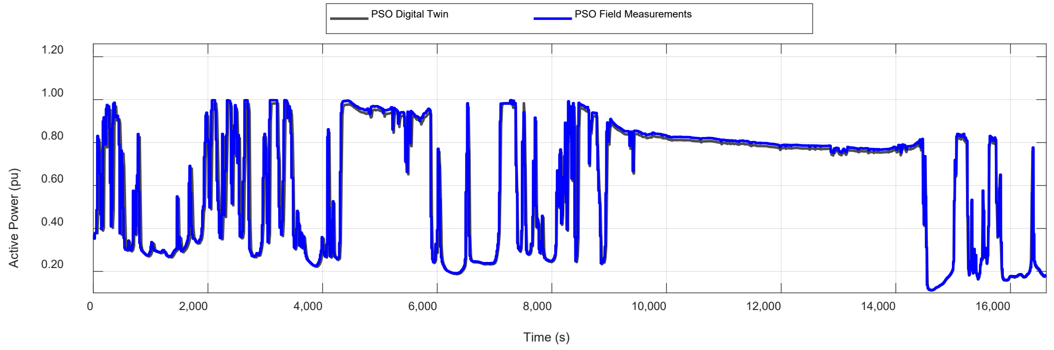


Fig. 40. Active Power Comparison.

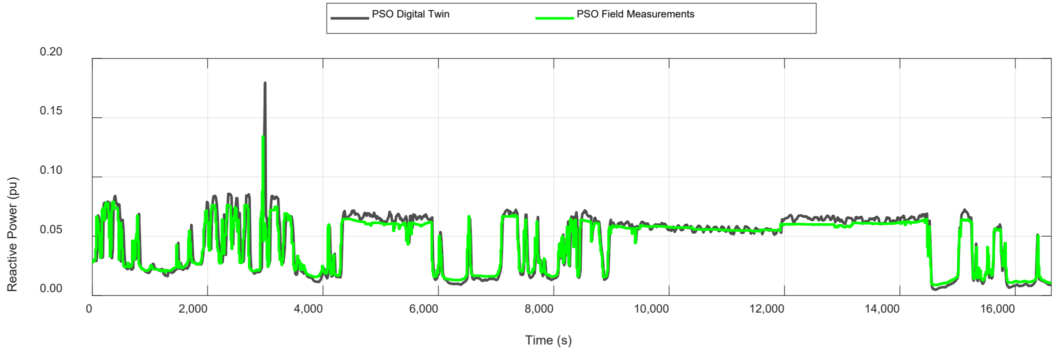


Fig. 41. Reactive Power Comparison.

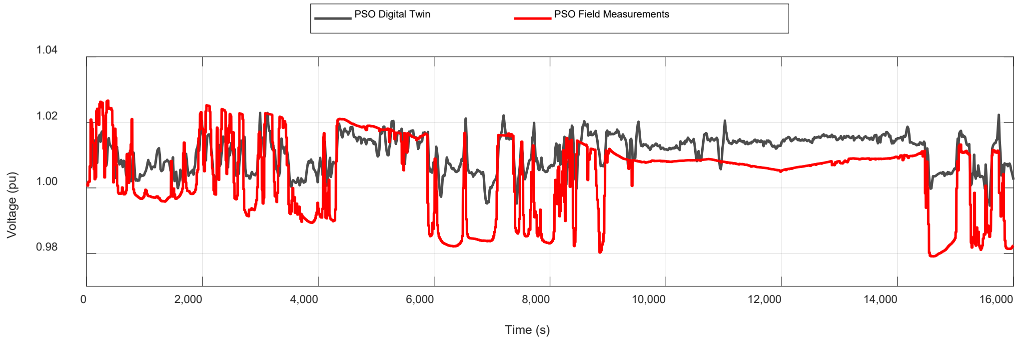
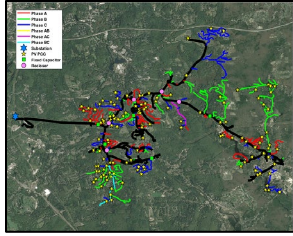


Fig. 42. Voltage Comparison.

Obtaining the NG Field Demonstration Results



All the voltage regulation methods were deployed on the live feeder by programming the VVC or power factor setpoints in the 28 PV inverters at Old Upton Road.

ESC demonstrates too much oscillation and voltage variability. PSO proves to be better.

Difficult to compare voltage regulation methods in the field because of different irradiance profiles due to performing tests on different days.

Note: Running PHIL helps overcome this limitations.

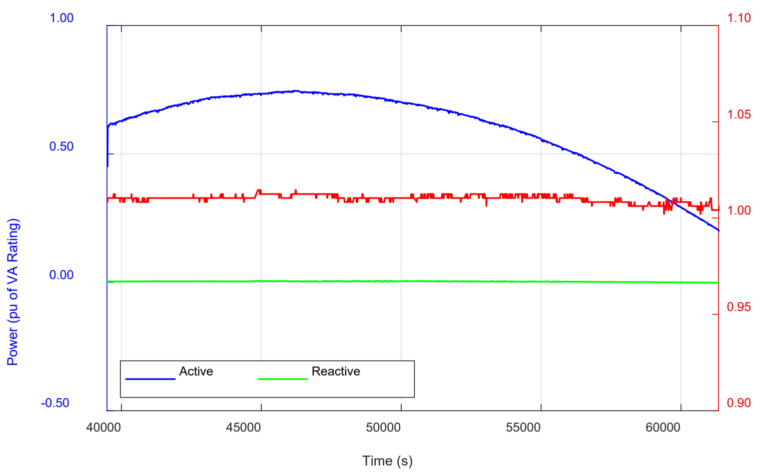


Fig. 43. Baseline Results at PV 1.

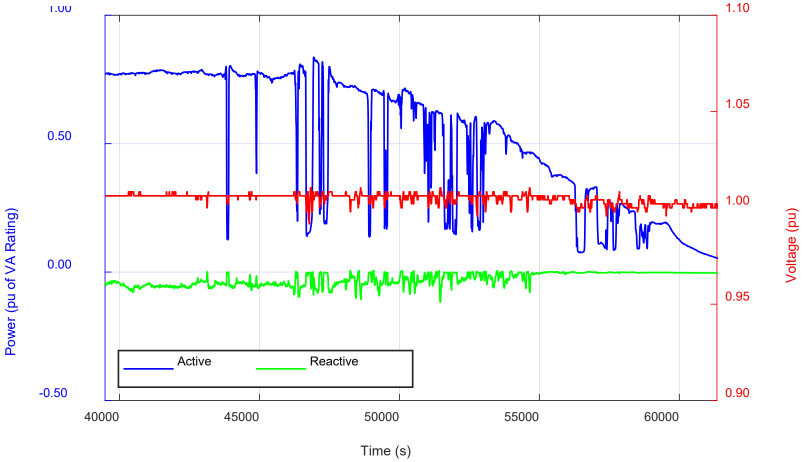


Fig. 44. VVC Results at PV 1.

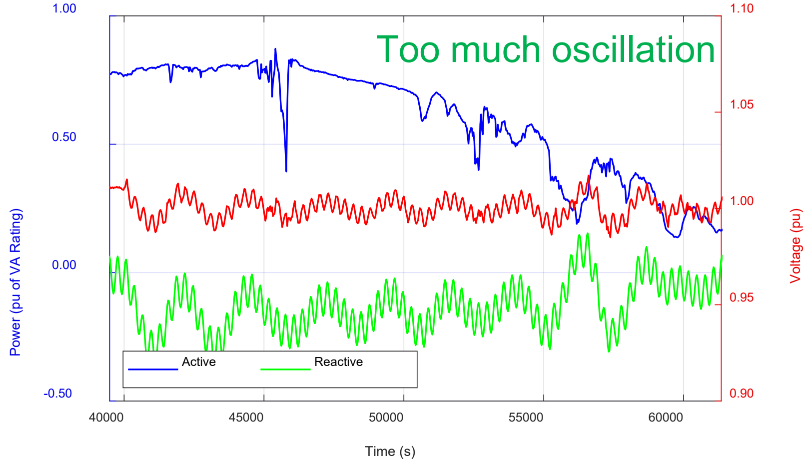


Fig. 45. ESC Results at PV 1.

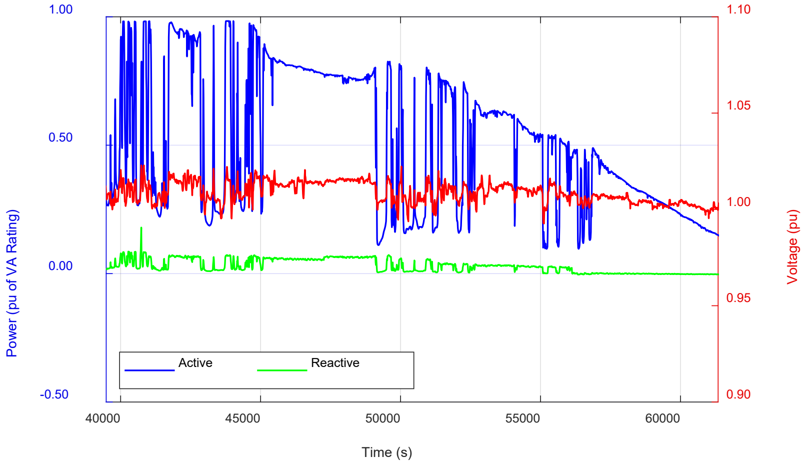


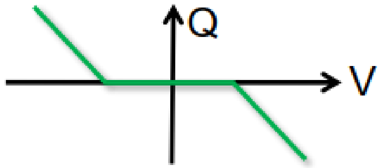
Fig. 46. PSO Results at PV 1.

Answer to Research Question

What are advantages and disadvantages of Volt Var Curve (VVC), Extremum Seeking Control (ESC) and Particle Swarm Optimization (PSO)?

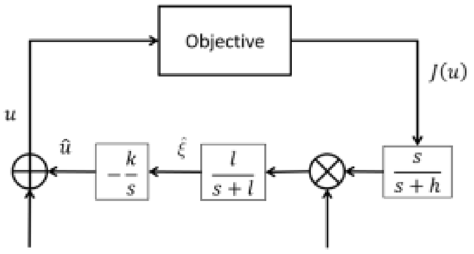
Volt-Var Curve (VVC)
- Function: <u>Volt-VAR</u>
- Pros: Simple, requires little or no communications, DER locations not needed
- Cons: Does not reach global optimum (because there is no optimization)

Volt-Var Mode



Extremum Seeking Control (ESC)
- Function: <u>New Grid-Support Function</u>
- Pros: Can achieve a solution for a given area (not just one bus)
- Cons: Could cause voltage distortion.

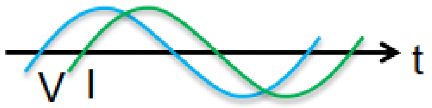
ESC



Particle Swarm Optimization (PSO)
- Function: <u>Power Factor or Reactive Power Commands</u>
- Pros: Direct influence over DER equipment for a given area.
- Cons: Requires telemetry, knowledge of DER locations, and state estimator/feeder model.

Note: Forecasting PV generation.
State estimating load behavior.

Adjust Power Factor



Contributions and Future Work

1. Comparison between different grid-support functions (MPPT, VVC, ESC and PSO) on the PNM and NG distribution feeder models (available on GitHub.com).

Note: ***Simulation*** results for MPPT, VVC, ESC and PSO functions were tested in a **RT** simulation environment.

Experimental results for MPPT and PSO functions were tested in a **RT-PHIL** simulation environment.

Field demonstration of MPPT, VVC, ESC and PSO functions was implemented in the actual NG feeder.

2. Comparison between RT simulation and **RT-PHIL** experimental results for MPPT and PSO is also presented.

3. These comparison has helped identify limitations of these grid-support as well as function approaches **RT-PHIL**.

Note: PV inverter location, PV inverter capacity, and amount of PV penetration into the system.

4. Future work: (1) a feeder with higher or lower local voltages would be more effective at directly comparing voltage regulation approaches, (2) it is also recommended that PV systems be developed that can provide zero and negative sequence currents so that phase imbalance can be corrected using three-phase PV systems.

The project is summarized in the following report:

J. Johnson, A. Summers, R. Darbali-Zamora, C. Hansen, M. J. Reno, Anya Castillo, S. Gonzalez, J. Hernandez-Alvidrez, N. S. Gurule, B. Xie, C. Zhong, A. P. Meliopoulos, C. Showalter, T. Rohrer, M. Rupnik, J. Anandan, N. Heine, M. E. Hernandez F., D. Montenegro Martinez, B. Seal, T. Tansy, B. Fox, A. Pochiraju, S. Martinez, H. Smith, S. Arafa, J. Woodard, J. Hawkins, P. Rothblum, M. Bintz and P. Chapman; **“Optimal Distribution System Voltage Regulation using State Estimation and DER Grid-Support Functions”**, SANDIA REPORT, June 2019.

Thank You

Rachid Darbali-Zamora

Senior Member of Technical Staff
Renewable and Distributed Systems Integration
Sandia National Laboratories
rdarbal@sandia.gov